Effect of amino acids and their derivatives on meat quality of finishing pigs

Xianyong Ma^{1,2,3,4,5} · Miao Yu^{1,2,3,4,5} · Zhichang Liu^{1,2,3,4,5} · Dun Deng^{1,2,3,4,5} ·
Yiyan Cui^{1,2,3,4,5} · Zhimei Tian^{1,2,3,4,5} · Gang Wang^{1,2,3,4,5}

Revised: 19 July 2019 / Accepted: 29 August 2019 / Published online: 4 September 2019
© Association of Food Scientists & Technologists (India) 2019

Abstract Amino acids provide key nutritional value, and significantly contribute to taste and flavor of meat. Here, we review the role of free amino acids in the muscle fibers in meat quality and sensory signals. We furthermore discuss how dietary supplementation of free amino acids and their derivatives (e.g. tryptophan, threonine, arginine, lysine, leucine, glutamate, threonine, sarcosine, betaines, and cysteamine) can influence these attributes. The available data shows that the quality of the meat is subject to the amino acids that are provided in the animal feed.

Keywords Amino acid · Meat quality · Finishing pig · Flavor · Amino acid derivatives

Introduction

There is a public demand to increase the quality and constituents of meat. Healthy, safe, and nutritious high-quality meat is increasingly demanded by consumers, in particular pork with rich flavor. Many factors affect the nutritional value and flavor of pork, such as the breed, nutrition, feeding method, and age of the animals. Meat encompasses a host of proteins, carbohydrates, lipids, and other nutritional constituents. Amino acids are not only essential components of proteins but also affect the synthesis of other components in the muscle. Furthermore, amino acids are important substances for the specific flavor of the meat (Chen and Liu 2004; Khan et al. 2015). The meat flavor components consist of both volatile substances and non-volatile substances as well as free amino acids (such as threonine, alanine, serine, lysine, proline, hydroxyproline, glutamic acid, aspartic acid, and arginine), which account for a high proportion. Due to the relatively high cost of amino acids, they are rarely used in practical applications toward improving pork quality (Lee et al. 2016; Shahidi 2001; Wasserman and Gray 2010). The effects of amino acids on meat quality are systematically reviewed in this study. This topic is of great significance toward improving the meat quality of pigs, which can be achieved via addition of appropriate amino acids and their derivatives. As a result of improvements in the amino acid production technology and the decreasing cost of relevant products, it has become increasingly feasible to use amino acids for the improvement of the meat quality. This method can positively enhance a healthy development of the pig industry and offers broad application prospects.

Xianyong Ma and Miao Yu are the first author.

✉ Xianyong Ma
maxianyong@gdaas.cn

✉ Gang Wang
lilymxy80@sohu.com

Miao Yu
394240809@qq.com

- ¹ Institute of Animal Science, Guangdong Academy of Agricultural Sciences, Guangzhou, China
- ² The Key Laboratory of Animal Nutrition and Feed Science, South China, Ministry of Agriculture, Guangzhou, China
- ³ State Key Laboratory of Livestock and Poultry Breeding, Guangzhou, China
- ⁴ Guangdong Key Laboratory of Animal Breeding and Nutrition, Guangzhou, China
- ⁵ Guangdong Engineering Technology Research Center of Animal Meat Quality and Safety Control and Evaluation, Guangzhou 510640, China

Effect of free amino acids in the muscle on meat quality and sensory traits

The content and composition of amino acids in meat is an important index for the evaluation of the nutritional value of pork and also affects the meat quality (Chen and Liu 2004). In addition, amino acids influence the sensory traits of pork. The degradation of peptides and amino acids in the meat improve its sensory traits and also improve taste (Khan et al. 2015). Hornstein and Crowe reported that flavor precursors were water-soluble small molecular substances that have been assumed to be components of amino acids and carbohydrates. Wasserman and Gray demonstrated that flavor precursors included amino acids, inosine, and polypeptides such as anserine and carnosine (Wasserman and Gray 2010). When the raw meat was heated, taurine, alanine, anserine, and carnosine decreased markedly, while ribose disappeared completely, indicating that amino acids, polypeptides, and carbohydrates were precursors of pork aroma. Glutamic acid is an important flavor of pork (Shahidi 2001). Histidine, arginine, methionine, valine, tryptophan, tyrosine, isoleucine, leucine, and phenylalanine are bitter (Lee et al. 2016), while alanine, serine, threonine, glycine, lysine, proline, and hydroxyproline are sweet (Shahidi 2001). Sodium glutamate and sodium aspartate are salty, while aspartic acid, glutamic acid, histidine, and asparagine are sour (Lee et al. 2016). The Maillard reaction plays an important role in the formation of meat color and flavor during the cooking process (Gong et al. 2016). Most flavor substances in food are products of the Maillard reaction, which involves a series of complex chemical reactions between carbonyl and amino compounds, such as reducing sugars and amino acids, and produces a variety of volatile flavoring compounds (Jalbout et al. 2007). Many heterocyclic compounds, aromatic compounds, and several aldehydes and ketones in the volatile compounds of pork are generally produced by the Maillard reaction between sugar and amino acids (Jalbout et al. 2007). The reaction between cysteine and sugar produces the characteristic pork flavor (Jayasena et al. 2013). The reaction between cysteine and glucose produces major sulfur compounds, while cysteine and glucose oxidize to produce pyrazine and furan (Tai and Ho 1997). Cysteine and ribose, as well as thiamin, have been shown to create compounds such as 2-methyl-3-furanthiol through the Maillard reaction (Mottram and Whitfield 1994). When meat is heated, sulfur-containing amino acids are degraded and transformed to hydrogen sulfide, methyl mercaptan, and methylthialdehyde, which further increases the aroma of meat during cooking (Zhang 2007). The presence of sulfur-containing amino acids produces sulfur compounds with a high odor threshold,

such as mercaptan and thiophene, which affect the formation of pyrazine and nitrogenous compounds (Lauridsen et al. 2006). Therefore, sulfur-containing amino acids are important precursors of volatile aromatic compounds. Sulfur-containing amino acids, such as lysine and cysteine, are responsible for the meat flavor produced during heat treatment. E.g., cysteine is a well-known precursor of sulfur-containing flavors in meat (Cerny and Davidek 2003). Similarly, reactions between cysteine, xylose, and glycine result in meat-like flavors. A fresh taste is a characteristic of meat and is attributed to aspartic acid, glutamic acid, and other salts of glutamine, asparagine, taste peptides, and nucleotides (such as inosinic acid) (Li and Zhu 2001). The specific taste of pork is mainly attributed to substances such as sodium glutamate and inosine monophosphate, which are important ingredients in fresh meat. It has been reported that no linear relationship was observed between the contents of inosinic acid and sodium glutamate and the taste of meat; however, a higher content of inosine-5'-monophosphate (IMP) in meat leads to a stronger taste (Normah et al. 2010).

Breed-specific content of the flavor compounds is related with free amino acids content in muscle

Different breeds of pigs have different genetic factors and body compositions, which results in different flavors. Contents of the total free amino acids, alanine, glutamate, glycine, aspartic acid, arginine, and inosine were higher in the meat of local breeds of pigs than in the meat of commercial pigs (Yang 2014). Yang also pointed out that the difference among the meat flavors of three types of local breeds of pigs (Anqing Six-White, Southern Anhui, and Dingyuan Black) and the DLY (Duroc × Landrace × Yorkshire) pig was caused by the free amino acids and inosinic acid. Due to the synergistic effect of inosine and glutamate, the flavor intensity was four times higher when both glutamic acid and inosine were present than when only glutamic acid was present and the synergistic effect increased with increasing glutamic acid concentration and identical inosinic acid concentration. Chen and Zeng investigated the flavor precursors and nutrients in the meat of Lailai pigs, Lulai black pigs, and large Yorkshire pigs (Chen et al. 2010). The reported results showed that the content of the flavor precursors was significantly higher in the Lailai pigs and Lulai black pigs than in the larger Yorkshire pigs. In particular, the intramuscular fat (IMF), IMP, and the amino acids responsible for flavor were much higher in the Lailai and Lulai black pigs. Zhu et al. (2013) reported that the contents of IMF, linolenic acid, inosine, glutamic acid, proline, and several flavor substances were more abundant in the Jiangqu Hai pig than in the DLY pig.

Yang et al. determined the amino acid composition of the Bamei, Landrace, and crossbred pigs. The reported results showed that the content of the various amino acids was significantly different among the three breeds. The taste of the meat of the Bamei pig is stronger due to its higher content of glutamic acid and other fresh amino acids in the muscle (Yang et al. 1994). Wu et al. (2009) determined the relationship between free amino acid contents and the taste of the meat in five breeds of pigs (Putian Black, Du Pu, Dapu, Duroc, and Yorkshire pigs). The free amino acid contents in these five breeds were 7.08%, 7.45%, 7.45%, 6.75%, 7.02%, and 7.34%, respectively. Glutamic acid, which was most closely related to the aspired taste, exhibited the highest amino acid content in the meat of the five breeds (2.87%, 2.98%, 2.66%, 2.80%, and 2.95%, respectively) and was suggested as the reason for the specific taste of pork. Wang et al. (2006) reported that the contents of flavor amino acids (glutamate, glycine, alanine, and aspartate) in hybrid wild pigs were significantly higher than in local white pork; furthermore, the pork quality of the hybrid wild pigs was better and the meat was more fragrant. Chen et al. (2016) determined the composition of free amino acids in four types of pigs: the Bama miniature pig, the Bama local pig, the Duroc pig, and the large white pig. The results showed that the contents of taurine, aspartic acid, glutamic acid, glycine, alanine, and carnosine were higher in the Bama miniature pig than in the Bama local pig, Duroc pig, and large white pig, and the resulting taste was also better. Therefore, it was concluded that the free amino acids in the meat affected the taste.

Effects of amino acids and their derivatives on meat quality

Many types of amino acids play an important role in pork flavor; therefore, the supplementation of amino acids to the feed can improve the pork flavor. The following amino acids play a key role for the pork flavor: tryptophan, threonine, arginine, lysine, and leucine.

Tryptophan

Tryptophan is essential for protein synthesis. L-tryptophan affects the RNA, fat, and protein metabolism in the animal liver; it also increases the protein synthesis in both the muscle and liver by stimulating the release of insulin. L-tryptophan is regarded as the third most important amino acid additive in animal feed after lysine and methionine. Several studies have shown that tryptophan improves the pork quality by alleviating stress in pigs. Pre-mortem stress can damage the pork quality and results in pale, soft, and exudative (PSE) meat. Tryptophan reduces stress by stimulating the secretion of

serotonin in the brain, which may be beneficial for the improvement of the pork quality (Schutte et al. 1995). Pethick et al. (1997) reported that supplementation of 0.5% tryptophan to the diet for 5 days before slaughter increased the concentration of 5-hydroxytryptamine in the hypothalamus, reducing the incidence and severity of PSE meat. Henry et al. (1996) reported that supplementation of 0.16% tryptophan stimulated the secretion of serotonin in the brain and delayed the decrease of the pH in the LD muscle. Ma et al. (2010) also reported that tryptophan enhanced the ability of pigs to resist stress and it also reduced the incidence of PSE meat. Adeola and Ball reported that although tryptophan alleviated stress in pigs, it had no effect on meat color, pH value, and the incidence of PSE meat. The effects of tryptophan on pork quality needs to be further investigated. In addition, the balance between tryptophan and other amino acids and the production of fecal odor through the fermentation of excess tryptophan by intestinal microorganisms may limit the application of tryptophan for the improvement of pork quality.

Threonine

Threonine, which is another essential amino acid in the muscle, is used for muscle protein synthesis. Feng et al. reported that supplementation of threonine in the feed significantly increased the growth, daily gain, feed conversion rate, and lean meat percentage of growing pigs and fattening pigs. The loin eye area and the content of protein in the LD muscle also increased significantly. The backfat thickness at the tenth rib increased with increased threonine content in the diet. The content of carcass fat and intramuscular fat in the LD muscle decreased linearly (Feng 1998). Hou et al. (2001) reported that adding a suitable level of threonine to the pig diet increased the protein content in the liver of pigs; different levels and proportions of amino acids in the diet were responsible for the protein deposition in animals. It has been suggested that the dietary protein could be decreased by 4% only when the lysine and threonine requirements were satisfied. According to this suggestion, the protein level in the pig diet was decreased by 4% when the diet was supplemented with synthetic amino acids; as a result, the backfat thickness of the pigs increased and the feed efficiency was improved (Easter and Baker 1980). Addition of threonine in an ideal protein system plays an important role. However, the detailed mechanism of the threonine involvement in protein synthesis remains unclear and requires further study.

Arginine

Arginine (Arg) is an important amino acid for protein synthesis. Supplementation of 1% Arg increased the body weight gain by 6.5% and the carcass skeletal-muscle

content by 5.5% while decreasing the carcass fat content by 11%. The LD muscle protein, glycogen, and fat contents also were increased by 4.8%, 42%, and 7%, respectively; in addition, the muscle pH 45 min post-mortem was increased by 3.2% and the muscle lactate content was decreased by 37%. Dietary Arg supplementation increased the IMF content in the LD muscle by 37.45% and in the biceps femoris (BF) muscle by 37.8%; it also increased the mRNA expression levels of the fatty acid synthase in the muscles (Tan et al. 2009), suggesting that Arg might promote IMF synthesis by upregulating the expression of key lipogenesis genes in the muscles (Tan et al. 2011). Ma et al. (2010) found that supplementation of 1% Arg in the diet significantly increased the IMF content and muscle redness of fattening pigs, decreased the muscle drip loss, and improved the muscle antioxidant ability. Addition of Arg to the diet also significantly increased the lean meat percentage and decreased the fat rate of fattening pigs so that the meat quality was partially improved. Wu et al. (2012) found that the lean meat percentage of Huanjiang Xiang pigs supplemented with 1% arginine increased by 15.0%, the fat rate decreased by 34.6%, and the crude fat content was decreased by 35.1% in the LD muscle, which indicated that arginine in the diet improved the carcass quality of Huanjiang Xiang pigs. Addition of 1% Arg to the diet of sows improved the meat quality of the sows' offspring (Gao 2011). Hu et al. (2017a, b) provided 1.0% Arg, 1% glutamic acid, or 1.0% Arg + 1.0% glutamic acid to the basal diet of growing finishing pigs for 60 days and found that the dietary supplementation of Arg and Glu increased the IMF deposition and improved both the meat color and fatty acid composition without affecting the growth performance and subcutaneous fat in pigs, thus providing a novel strategy to enhance the meat quality in growing-finishing pigs. However, Go et al. (2012) found that dietary Arg supplementation did not increase the IMF in pigs. Madeira et al. (2015) found that supplementation with betaine and Arg to lysine-deficient diets did not increase the IMF content but improved the pork's sensory traits, including overall acceptability and meat tenderness. It is possible that the IMF was affected by other factors such as the environment and feed conditions.

Lysine

The reports on the effect of lysine on meat quality are not consistent and there are many specific reasons, mainly heredity, environment, and nutrition. Lysine enhances the appetite, diseases the resistance of livestock and poultry, and participates in fat metabolism; however, the effect of lysine on meat muscle fat and carcass quality differs under different conditions (Wang et al. 2014). According to the National Research Council (NRC) (1998), the protein

requirement for optimum growth performance is 18% for growing pigs and 15.5% for fattening pigs. The lysine requirement is 0.95% for growing pigs and 0.75% for fattening pigs. However, with regard to pork quality, low protein and lysine contents in the diet increased the content of IMF in pork (Zhang et al. 2011). Whipple reported that dietary lysine supplementation did not affect muscle fiber types; it increased the diameter and volume of several muscle fibers and also increased the area of the LD muscle while reducing the juiciness and tenderness of the muscle (Whipple 1992). Essen-Gustavsson et al. (1994) reported that a reduction in dietary protein from 18% in growing pigs to 15% in fattening pigs and in dietary lysine from 0.96% in growing pigs to 0.64% in fattening pigs resulted in an increase in the IMF of the LD muscle from 1.5% to 2.5% at an increasing rate of 66.7%. Wang et al. (2012) also reported that an increase in the dietary crude protein level decreased the carcass backfat thickness, the marbling, and the tenderness of the meat while also increasing the lean meat rate; however, low protein and low lysine contents increased the IMF content of pork. Chen (2012) also reported that the IMF content of pigs could be increased by feeding diets with low protein and lysine contents. Li (2010) reported that when pigs received a lysine-deficient diet, the carcass fat content decreased and when dietary lysine was added to the diet of fattening pigs, the muscle volume, the area of the LD muscle, and the diameter of the muscle fiber increased; however, the muscle juiciness and tenderness decreased. Gong and Ma (1993) studied the lysine requirements of lean growing pigs and reported that the carcass quality of the pork was improved when cotton kernel meal was used as sole protein feed; the actual content of lysine acid in the diet was 0.69%. In addition, the energy in the diet also influenced the effects of lysine and the fat content in the muscle decreased when the ratio of lysine to energy increased (Castell et al. 1994). (De la Llata et al. 2002) found that an increase in the concentration of lysine in a sorghum-soybean diet decreased the daily gain and lean meat rate and increased the thickness of the back fat. However, an increase in the concentration of lysine in a corn-soybean diet had did not affect the carcass traits. The effect of lysine on meat quality is influenced by many factors such as protein and energy levels, dietary type, and pig breeds. To obtain the best growth performance and carcass composition, the ratio of lysine to energy or protein should be higher than the ratios currently used in the pig industry (Apple et al. 2004).

Leucine

Leucine, also called L-leucine, is a type of branched-chain amino acid and an essential amino acid that must be supplied by the diet. Leucine regulates the intracellular signal

pathways of muscle cells, thus enhancing the protein synthesis in mammalian skeletal muscle (Kim Ball et al. 2002). Cisneros et al. (1996) also reported that high levels of leucine were used for fat synthesis and increased the muscle fat percentage. Although leucine increased the IMF deposition, excessively high levels of leucine weakened the utilization of other amino acids mainly because they are transported in the same manner or because leucine induces protein synthesis (Hyun et al. 2003). Luo et al. (2017) added 0.14% isoleucine to the diet of fattening pigs (which exceeds the NRC recommended level of 0.14%) and found that drip loss, shear force, and yellowness of the muscle decreased, while the IMF content increased. Dean et al. (2005) added isoleucine to a corn-soybean meal diet and reported that the backfat thickness, total fat content, and body fat percentage of fattening pigs increased without affecting the loin muscle area and slaughter rate. Several studies have suggested that the IMF of pork can be increased by feeding finishing pigs high levels of leucine or high levels of leucine in combination with low levels of lysine (Hyun et al. 2007). However, high levels of leucine in combination with a normal protein diet did not affect the meat quality of finishing pigs except for meat tenderness (Hyun et al. 2003). Sugawara et al. (2009) also reported that a protein-free diet supplemented with leucine did not increase the protein synthesis. Madeira et al. (Madeira et al. 2014) found that leucine addition to the diet of growing-finishing pigs did not affect the IMF content, backfat thickness, and loin weight but increased the juiciness. Zhang et al. (2016) suggested that decreasing the dietary protein from 14.5% to 10% with leucine supplementation improved the meat quality and increased the net protein deposition. However, a high dose of leucine supplementation in the diet led to a decrease in feed intake and performance of the pigs, suggesting that a diet with less than 2% leucine supplementation was appropriate (Hyun et al. 2003).

Other amino acids

In Addition the amino acids mentioned above, glutamate and threonine also improve the meat quality of pigs.

Glutamic acid is one of the most important flavor amino acids in muscle. Hu et al. (2017a) showed that glutamic acid supplementation could reduce backfat thickness, it also improved muscle fatty acid composition (Hu et al., 2017b). Zhou et al. (2014) found that monosodium L-glutamate increased intramuscular fat content. Kong et al. (2015) reported that 1.00% Leucine could increase the intramuscular fat content in longissimus dorsi muscle and biceps femoris, and did not affect the growth performance of fattening pigs. After adding 1.00% glutamic acid, the backfat thickness of finishing pigs decreased by 34.3%,

while the addition of 1.00% Leucine plus 1.00% glutamic acid increased the intramuscular fat content of biceps femoris, and did not affect the growth performance of fattening pigs.

As an essential amino acid in pigs, threonine also enhances the immunity of pigs, increase weight gain and feed intake, and improve carcass quality. But the proper ratio of threonine to lysine in finishing pigs feed is 0.65–0.68 (Plitzner et al. 2007). In addition to being used as nutrients to satisfy animal growth needs, amino acids also increase pork flavor or regulate metabolic pathways to improve pork quality as regulatory additive. At present, just one single amino acid or two amino acids combination improving meat quality having been reported. There is no related reports about how to use these amino acids together, and what is the appropriate proportion of these amino acids? With the development of synthetic amino acid industry, the popularization and application of these functional amino acids are more and more. The effect and proportion of combined addition need to be studied, which is helpful to further rational application of amino acids to improve meat quality.

Derivatives of amino acids

Sarcosine

Sarcosine is a tripeptide that is synthesized from arginine, glycine, and methionine in the presence of ATP. 65% of sarcosine in animals is stored in muscles where sarcosine acts as an “energy bank”. The sarcosine content in the muscle can be increased by adding sarcosine monohydrate to the feed. The increase of the muscle sarcosine content increases the water content of the muscle fiber, the muscle volume, and the hydraulic capacity of the muscle system (Berg and Allee 2001). Several reports indicated that the addition of sarcosine monohydrate to the diet also lowered the accumulation of lactic acid. In addition, the increase in the sarcosine content in the muscle increased the water content of the muscle fiber, the muscle volume, and the muscle hydraulic capacity (Berg and Allee 2001). Furthermore, sarcosine increases the pH value at 45 min postmortem and reduces the L* value. However, the results of recent experiments are not consistent with this conclusion (Berg et al. 2003; Stahl and Berg 2003). The specific effects of sarcosine on meat quality, the amount of sarcosine that should be added to the feed, and the appropriate supplementation time require further research. It has also been reported that creatine or its precursor, guanidinoacetate, can substitute part of the Arg in poultry diets (Baker 2009; Dilger et al. 2013) and that guanidinoacetate is an

effective creatine precursor in swine (McBreairty et al. 2015).

Betaine

Betaine, or trimethylglycine, is a very effective methyl donor. Dietary supplementation of betaine (trimethylglycine) may improve the nitrogen and energy utilization efficiency of pigs (Eklund et al. 2005). This is likely because betaine is a methyl donor involved in many important animal methylation reactions. Wang et al. (2000) found that 1 g/kg of betaine significantly reduced fat deposition and increased the lean meat rate in pigs while also increasing the myoglobin and IMF content. Matthews et al. (2001) also found that dietary supplementation of betaine at 45 min postmortem increased the pH value and decreased the drip loss of the meat. Eklund et al. (2005) showed that addition of 1 g/kg guanidine acetic acid or 1 g/kg guanidyl acetate plus 0.5 g/kg betaine in fattening pig feed significantly increased the daily gain, decreased the average backfat thickness, delayed the decrease in the pH value, increased the water holding capacity and tenderness of the meat, and thus improved the overall meat quality. Madeira et al. (2015) reported that betaine and Arg supplementation of Lys-deficient diets improved the pork sensory traits, including the overall acceptability. Martins et al. (2012) determined that long-term (1 g/kg, 20 weeks) supplementation of betaine in pig feed selectively increased the intramuscular lipid deposition without affecting other chemical and physical characteristics of the muscles, such as the color of the meat or body fat deposition. Matthews et al. (2001) reported that 0.25% dietary betaine decreased the backfat thickness, L value, cooking loss, and increased the pH value. Based on these results, it has been concluded that 0.25% betaine improved the pork quality. However, opinions on the effect of betaine on pork quality differ and the effectiveness may depend on the animal trial conditions (Dugan et al. 2004).

Cysteamine

As an inhibitor of somatostatin (SS), cysteamine specifically binds to SS in vivo and in vitro, decreases the SS levels in vivo, increases the growth hormone (GH) level, and promotes the growth of livestock and poultry. Many studies have shown that cysteamine decreases the SS level, regulates the hormone level, redistributes nutrients, and improves animal performance. The effects of cysteamine on growth promotion were optimal in the range of appropriate dosages and the effects differed for different growth stages. Fu showed that addition of 50–100 mg/kg cysteamine during the growth period improved the feed efficiency and did not affect the growth performance;

however, the SS in the serum decreased and the GH increased significantly (Fu 2004). The amino acid content in the muscle also significantly increased. The carcass and meat quality improved. Dunshea added 700 mg/kg cysteamine to the diet of fattening pigs (female) and the results showed that the carcass weight was higher in the experimental group than in the control group; the lean meat percentage increased, and the backfat thickness decreased significantly (Dunshea 2000). Yang et al. (2005) added 30–50 mg/kg cysteamine to the diet of fattening pigs and demonstrated that the backfat thickness decreased while the carcass quality increased significantly. Wei et al. (2003) showed that 180 mg/kg cysteamine significantly increased the lean meat rate and muscle color score, and decreased the fat deposition significantly. Chen et al. (2004) also reported that 60–75 mg/kg cysteamine significantly increased the lean meat rate and decreased the fat deposition; however, it had no effect on other meat quality indices. The effect of cysteamine on pork quality may be related to the dosage of cysteamine. Qin et al. (2017) reported that the meat quality of Ningxiang pigs was improved by increasing the content of linoleic acid and decreasing stearic acid in meat when 80 mg/kg cysteamine was added to the pig feed. Bai et al. (2017) found that dietary supplementation with cysteamine hydrochloride improved the antioxidant status and delayed the meat discoloration by improving the glutathione levels and antioxidase activity after extended chill storage (for 48 h after slaughter). Due to the different processing forms of cysteamine, the effects may differ; therefore, the determination of the appropriate dose is based on the product form and experimentally obtained results; generally, an amount from tens of grams to hundreds of grams is appropriate.

Discussion

Meat is only fragrant when it is heated due to a complex series of changes that occur during heating and produce volatile flavor substances, such as lactone compounds, pyrazine compounds, furan compounds, and sulfides. Ding reported that water-soluble saccharide, amino acid-containing compounds and lipid substances are precursor substances of these fragrant compounds. Although the lipid tissue contributed to the unique meat flavor, if fat was removed from a variety of meat products, the meat flavor was consistent and no difference was observed (Ding 1996). Therefore, it has been concluded that amino acids are very important for meat quality. In this paper, we only review the effects of amino acids on meat quality.

Amino acids have specific flavors; for example, aspartic acid, glutamic acid, histidine, and asparagine are sour. Histidine, arginine, methionine, valine, tryptophan,

tyrosine, isoleucine, leucine, and phenylalanine are bitter. Alanine, serine, threonine, glycine, lysine, proline, and hydroxyproline are sweet. Sodium glutamate and sodium aspartate are salty (Lee et al. 2016). Sulfur-containing amino acids, cysteine, cysteine, and glutathione are essential for the production of aroma compounds. Werkhoff et al. (1990) reported the aroma compounds of a meat model system comprised of thiamine, cysteine, glutamate, ascorbic acid, and water. The reaction was performed under the conditions of pH 5 and 120 °C for 0.5 h; 70 sulfur compounds were obtained and 19 produced savory meat flavor. Therefore, it was suggested that these amino acids should be used as pork seasoning for meat.

In addition, amino acids participate in the Maillard reaction and produce many flavor compounds. Although not all Maillard reaction products contain meat flavor compounds, the Maillard reaction plays a central role in the formation of flavor compounds. The reaction products include sulfide, furan, pyrrole, thiophene, imidazole, pyridine, and cyclohexene sulfide and other low molecular weight precursors; among these, sulfides are especially important and it has been shown that the meat flavor almost disappeared when sulfides were removed from the volatile compounds during the process of meat heating (Cai et al. 2002). Protein also affects the meat flavor because it degrades into amino acids during the heating process. Many reports showed that the structural changes caused by protein degradation are very complex; an example is carbonylation, the breaking of the main chain of peptides, and the formation of inter-molecular disulfide bonds, which are basic mechanisms that are responsible for the structural changes of proteins. The carbonylation and hydroxylation of the side chain of amino acid residues are the main mechanisms that affect changes in protein oxidation (Jiang and Xiong 2013; Liu et al. 2000). Protein conformational changes expose several amino acid groups, such as sulfur-containing amino acids. During the heating or processing of pork, the concentration of free amino acids is several times or even a dozen times higher than that of fresh meat. Free amino acids produce important volatile flavor substances, such as alcohols, aldehydes, and ketones via degradation or reactions with other substances (Toldra 1998).

The types and contents of free amino acids in pork vary for different pig breeds, resulting in differences in the pork flavor. Several reports showed a positive correlation between pork flavor and amino acid content (Chen et al. 2010; Wang et al. 2006; Wu et al. 2009; Yang et al. 1994; Zhu et al. 2013). Therefore, the supplementation of free amino acids or their derivatives to pig feed is a potential method with which to improve the pork flavor and meat quality. Amino acids and their derivatives not only increase the concentration of free amino acids but are also

responsible for important physiological functions, such as antioxidant function, reducing stress, improving the immune function, and indirectly improving the meat quality.

In summary, amino acids and their derivatives contribute significantly to the meat quality. To better utilize amino acids for the improvement of the meat quality, further research is required specifically investigating the following aspects: a simpler and more convenient industrial model of amino acid production is required for a wider application; the synergistic effects of various amino acids on the improvement of meat quality require further study; furthermore, the production of amino acid metabolites or analogs, their use in animal production, and their effects on meat quality should be actively explored.

Acknowledgements We thanks for all authors to participate in writing and editing this article.

Author contributions All authors are involved in the review, reading and summary of the literature. XM and MY are responsible for writing- original draft preparation, DD, YC and ZT are responsible for looking for references, XM is responsible for funding acquisition, GW is responsible for reviewing and editing, ZL help to edit this manuscript.

Funding This research was funded by grants from the Guangdong Modern Agro-industry Technology Research System (2017LM1080), the Guangdong modern agricultural industrial technology extension system (2017LM4164, 2018LM2153), National Key Research and Development Program of China (2016YFD0501210), and the key project of Guangzhou City (201707020007).

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

Human and animal rights This research was not involved human participants and/or animals.

References

- Apple JK, Maxwell CV, Brown DC, Friesen KG, Musser RE, Johnson ZB, Armstrong TA (2004) Effect of dietary lysine and energy density on performance and carcass characteristics of finishing pigs fed ractopamine. *J Anim Sci* 82:3277–3287
- Bai M, Liu H, Xu K, Zou B, Yu R (2017) Effects of dietary coated cysteamine hydrochloride on pork color in finishing pigs. *J Sci Food Agric* 48(1):96–100
- Baker DH (2009) Advances in protein amino acid nutrition of poultry. *Amino Acids* 37(1):29–41
- Berg EP, Allee GL (2001) Creatine monohydrate supplemented in swine finishing diets and fresh pork quality: I. A controlled laboratory experiment. *Anim Sci* 79:3075–3080
- Berg EP, Maddock KR, Linville ML (2003) Creatine monohydrate supplemented in swine finishing diets and fresh pork quality: III. Evaluating the cumulative effect of creatine monohydrate and alpha-lipoic acid. *J Anim Sci* 81:2469–2474

- Cai MY, Li B, Yuan XH (2002) A survey of research on meat-flavor essence. *Cold Drink Quick-frozen Food Ind* 4:40–44 (**in Chinese**)
- Castell AG, Cliplet RL, Posteflynn LM, Butler G (1994) Performance, carcass and pork characteristics of castrates and gilts self-fed diets differing in protein content and lysine:energy ratio. *Can J Anim Sci* 74(3):519–528
- Cerny C, Davidek T (2003) Formation of aroma compounds from ribose and cysteine during the Maillard reaction. *J Agric Food Chem* 51(9):2714–2721
- Chen YZ (2012) Evaluation of pork quality and its influencing factors. *Chin Anim Husb Vet Med* 7:155–158 (**in Chinese**)
- Chen GH, Liu MZ (2004) Analysis of muscle nutrition characteristics of wild pig hybrids. *Pig breeding* 1:24–27
- Chen AG, Hong QH, Wu LY (2004) Effect of cysteamine on carcass quality in growing finishing pigs and its mechanism. *Chin Anim Husb* 40(2):11–13 (**in Chinese**)
- Chen QM, Zeng YQ, Wei SD, Li H, Song YP (2010) Studies on the characteristics of muscle flavor precursors and their nutrition and edible quality of different pig breeds. *J Zhejiang Univ Agric Life Sci* 36(3):299–305 (**in Chinese**)
- Chen QH, Xu H, Huang DP (2016) Analysis of free amino acids in Bama pork and three different kinds of pork. *J Anhui Agric Sci* 44(6):97–99
- Cisneros F, Ellis M, Baker D, Easter R MF (1996) The influence of short-term feeding of amino acid-deficient diets deficient diets and high dietary leucine levels on the intramuscular fat content of pig muscle. *Anim Sci* 63:517–522
- De la Llata M, Dritz SS, Tokach MD, Goodband RD, Nelssen JL (2002) Effects of increasing L-lysine HCl in corn- or sorghum-soybean meal-based diets on growth performance and carcass characteristics of growing-finishing pigs. *J Anim Sci* 80(9):2420–2432
- Dean DW, Southern LL, Kerr BJ, Bidner TD (2005) Iso-leucine requirement of 80- to 120-kilogram barrows fed corn-soybean meal or corn-blood cell diets. *J Anim Sci* 83(11):2543–2553
- Dilger RN, Bryant-Angeloni K, Payne RL, Lemme A, Parsons CM (2013) Dietary guanidino acetic acid is an efficacious replacement for arginine for young chicks. *Poult Sci* 92(1):171–177
- Ding N (1996) Food flavor chemistry. China Light Industry Press, Beijing
- Dugan ME, Aalhus JL, Uttaro B (2004) Nutritional manipulation of pork quality: current opportunities. *Adv Pork Prod* 15:237–243
- Dunshea FR (2000) Porcine somatotropin and cysteamine hydrochloride improve growth performance and reduce back fat in finisher gilts. *Aust J Exp Agric* 47(7):796–800
- Easter RA, Baker DH (1980) Lysine and protein levels in corn-soybean meal diets for growing-finishing swine. *J Anim Sci* 50:467
- Eklund M, Bauer E, Wamatu J, Mosenthin R (2005) Potential nutritional and physiological functions of betaine in livestock. *Nutr Res Rev* 18:31–48
- Essen-Gustavsson B, Karlsson A, Lundstrom K, Enfalt AC (1994) Intramuscular fat and muscle fibre lipid contents in haloethane-gene-free pigs fed high or low protein diets and its relation to meat quality. *Meat Sci* 38:269–277
- Feng WX (1998) Effect of increasing dietary threonine level on the production performance of growing fattening pigs. *Guangxi Anim Husb Vet Med* 4:49–51 (**in Chinese**)
- Fu JM (2004) Effects of different doses of cysteamine on growth performance, hormones, carcass and meat quality of growing finishing pigs. Master thesis of Shenyang Agri University
- Gao KG (2011) Effects of arginine supplementation on reproductive performance and muscle development of offspring in sows. Ph. D. thesis of South China Agri University (**in Chinese**)
- Go G, Wu G, Silvey DT, Choi S, Li X, Smith SB (2012) Lipid metabolism in pigs fed supplemented conjugated linoleic acid and/or dietary arginine. *Amino Acids* 43:1713–1726
- Gong YS, Ma CG (1993) Study on Lysine requirement of lean growing pigs. *Chin Feed* 4:10–11 (**in Chinese**)
- Gong JX, Cao CC, Hou L, Du RQ, Zhang L, Xie JC, Sun BG (2016) The initial-Maillard pathway to meat flavor during the preparation of thermal reaction meat flavorings. *J Chin Inst Food Sci Technol* 16(2):68–75 (**in Chinese**)
- Henry Y, Seve B, Mounier A, Ganier P (1996) Growth performance and brain neurotransmitters in Pigs as affected by tryptophan, protein, and sex. *J Anim Sci* 74:2700–2710
- Hou YQ, Lv MZ, Wo YM (2001) Effects of levels of methionine and threonine on protein metabolism in early weaning piglets. *Feed Res* 7:7–8 (**in Chinese**)
- Hu CJ, Jiang QY, Zhang T, Yin YL, Li FN, Deng JP, Wu GY, Kong XF (2017a) Dietary supplementation with arginine and glutamic acid modifies growth performance, carcass traits, and meat quality in growing-finishing pigs. *J Anim Sci* 95(6):2680–2689
- Hu CJ, Jiang QY, Zhang T, Yin YL, Li FN, Su JY, Wu GY, Kong XF (2017b) Dietary supplementation with arginine and glutamic acid enhances key lipogenic gene expression in growing pigs. *J Anim Sci* 95(12):5507–5515
- Hyun Y, Ellis M, McKeith FK, Baker DH (2003) Effect of dietary leucine level on growth performance, and carcass and meat quality in finishing pigs. *Can J Anim Sci* 83:315–318
- Hyun Y, Kim JDM, Peterson BA, Baker DH, McKeith FK (2007) Effect of dietary leucine and lysine levels on intramuscular fat content in finishing pigs. *Can J Anim Sci* 87:303–306
- Jalbout AF, Shipar MAH, Navarro JL (2007) Density functional computational studies on ribose and glycine Maillard reaction: formation of the Amadori rearrangement products in aqueous solution. *Food Chem* 103(3):919–926
- Jayasena DD, Ahn DU, Nam KC, Jo C (2013) Flavour chemistry of chicken meat: a review. *Asian Aust J Anim Sci* 26(5):732–742
- Jiang J, Xiong YL (2013) Extreme pH treatments enhance the structure-reinforcement role of soy protein isolate and its emulsions in pork myofibrillar protein gels in the presence of microbial transglutaminase. *Meat Sci* 93(3):469–476
- Khan MI, Jo C, Tariq MR (2015) Meat flavor precursors and factors influencing flavor precursors: a systematic review. *Meat Sci* 110:278–284
- Kim Ball SR, Farrell PA, Jefferson LS (2002) Exercise effects on muscle insulin signaling and action invited review: role of insulin in translational control of protein synthesis in skeletal muscle by amino acids or exercise. *J Appl Phys* 93:1168–1180
- Kong XF, Zhou XL, Feng ZM, Li FN, Ji YJ, Tan BE, Liu YY, Geng MM, Wu GY, Blachier F, Yin YL (2015) Dietary supplementation with monosodium L-glutamate modifies lipid composition and gene expression related to lipid metabolism in growing pigs fed a normal-or high-fat diet. *Livest Sci* 180:247–252
- Lauridsen L, Miklos R, Schäfer A, Aaslyng MD, Bredie WLP (2006) Influence of added carbohydrates on the aroma profile of cooked pork. *Dev Food Sci* 43:355–358
- Lee CW, Lee JR, Kim MK, Jo C, Lee KH, You I, Jung S (2016) Quality improvement of pork loin by dry aging. *Korean J Food Sci Anim Resour* 36(3):369–376
- Li WY (2010) Regulation of feed nutrients on quality of animal products. *Chin Anim Husb Vet Surg* 8:237–240 (**in Chinese**)
- Li J, Zhu GB (2001) Flavor of meat and aquatic products (2nd Edition) Beijing; J Chin Light Industry 1–90 (**in Chinese**)
- Liu G, Xiong YL, Butterfield DA (2000) Chemical, physical, and gel-forming properties of oxidized myofibrils and whey-and soy-protein isolates. *J Food Sci* 65(5):811–818
- Luo YH, Zhang X, Qin CF, Jiao N, Yin JD (2017) Effects of dietary isoleucine levels on growth performance, carcass traits and meat

- quality of fattening pigs. *Chin Anim Nutr* 29(6):1884–1894 (**in Chinese**)
- Ma XY, Lin YC, Jiang ZY, Zheng CT, Zhou GL, Yu DQ, Cao T, Wang J, Chen F (2010) Dietary arginine supplementation enhances antioxidative capacity and improves meat quality of finishing pigs. *Amino Acids* 38:95–102
- Madeira MS, Alfaia CM, Costa P, Lopes PA, Lemos JP, Bessa RJ, Prates JA (2014) The combination of arginine and leucine supplementation of reduced crude protein diets for boars increases eating quality of pork. *J Anim Sci* 92(5):2030–2040
- Madeira MS, Alfaia CM, Costa P, Lopes PA, Martins SV, Lemos JP, Moreira O, Santos-Silva J, Bessa RJ, Prates JA (2015) Effect of betaine and arginine in lysine-deficient diets on growth, carcass traits, and pork quality. *J Anim Sci* 93(10):4721–4733
- Martins JM, Neves JA, Freitas A, Tirapicos JL (2012) Effect of long-term betaine supplementation on chemical and physical characteristics of three muscles from the Alentejano pig. *J Sci Food Agric* 92(10):2122–2127
- Matthews JO, Southern LL, Higbie AD, Persica MA, Bidner TD (2001) Effects of betaine on growth, carcass characteristics, pork quality, and plasma metabolites of finishing pigs. *J Anim Sci* 79(3):722–728
- McBreairty LE, Robinson JL, Furlong KR, Brunton JA, Bertolo RF (2015) Guanidinoacetate is more effective than creatine at enhancing tissue creatine stores while consequently limiting methionine availability in yucatan miniature pigs. *PLoS ONE* 10(6):e0131563
- Mottram DS, Whitfield FB (1994) Aroma volatiles from meat-like Maillard systems. In: Parliament TH, Morello MJ, McGorin RJ (eds) Thermally generated flavors-Maillard, microwave and extrusion processes, vol 543. ACS symposium series. Wiley, Hoboken, pp 180–191
- Normah I, JamUan B, Saarin N, Che MY (2010) Chemical and taste characteristics of threadfin bream (*Nemipterus japonicus*) hydrolysate. *J Sci Food Agric* 84(11):1290–1298
- Pethick DW, Warner RD, D'Souza DN, Dunshea FR (1997) Nutritional manipulation of meat quality. In: Manipulating pig production. Australian Pig Science Association, vol. 5, pp. 110–115
- Plitzner C, Ettle T, Handl S, Schmind P, Windisch W (2007) Effects of different dietary threonine levels on growth and slaughter performance in finishing pigs. *Czech J Anim Sci* 52(12):447–455
- Qin LS, Xing YT, Zhang Y, Shu XG, Chen YG (2017) Effects of cysteamine on carcass traits and meat quality of Nanjing Pigs. *Chin J Anim Nutr* 29(9):3325–3330
- Schutte JB, Verstraten AJMA, Lenis NP, Jong JD, Diepen JTMV (1995) Requirement of young pigs for apparent ileal digestible tryptophan. *Neth J Agri Sci* 43(3):287–296
- Shahidi F (2001) The flavor of meat and aquatic products. Version 2, vol 1–10. China Light Industry Press, Beijing, pp 54–69
- Stahl CA, Berg EP (2003) Growth parameters and meat quality of finishing hogs supplemented with creatine monohydrate and a high glycemic carbohydrate for the last 30 days of production. *Meat Sci* 64:169–174
- Sugawara T, ItoY NN, Nagasawa T (2009) Regulation of muscle protein degradation, not synthesis, by dietary leucine in rats fed a protein-deficient diet. *Amino Acids* 37:609–616
- Tai CY, Ho CT (1997) Influence of cysteine oxidation on thermal formation of Maillard aromas. *J Agric Food Chem* 45(9):3586–3589
- Tan B, Yin Y, Liu Z, Li X, Xu H, Kong X, Huang R, Tang W, Shinzato I, Smith SB, Wu G (2009) Dietary L-arginine supplementation increases muscle gain and reduces body fat mass in growing-finishing pigs. *Amino Acids* 37(1):169–175
- Tan B, Yin Y, Liu Z, Tang W, Xu H (2011) Dietary L-arginine supplementation differentially regulates expression of lipid-metabolic genes in porcine adipose tissue and skeletal muscle. *J Nutr Biochem* 22:441–445
- Toldra F (1998) Proteolysis and lipolysis in flavour development of dry-cured meat products. *Meat Sci* 49:101–110
- Wang YZ, Xu ZR, Feng J (2000) Effects of betaine on pork quality and its mechanism. *Chin Agric Sci* 33(1):94–99 (**in Chinese**)
- Wang YH, Ma LZ, Zhang JR, Zhang YJ (2006) Study on nutritional quality of crossbred wild boar and native white pork. *J Agric Prod Proc* 52(1):11–14
- Wang YH, Wang JC, Wen QH (2012) Study on the application of pork quality control technology. *Chin Pig Ind* 6:51–55 (**in Chinese**)
- Wang LQ, Zhou WL, Sun YH (2014) Factors affecting pork quality and improvement methods. *Pig Sci* 7:124–125 (**in Chinese**)
- Wasserman AE, Gray N (2010) Meat flavor. I. Fractionation of water-soluble flavor precursors of beef. *J Food Sci* 30:801–807
- Wei XH, Xia D, Gao QX (2003) Effects of cysteamine on carcass and meat quality of finishing pigs. *J Nanjing Agric Univ* 26(3):73–75 (**in Chinese**)
- Werkhott P, Bruning J, Emberger R, Guentert M, Koepsel M (1990) Isolation and characterization of volatile sulfur-containing meat flavor components in model systems. *J Agric Food Chem* 38:777–791
- Whipple TL (1992) The role of arthroscopy in the treatment of wrist injuries in the athlete. *Clin Sports Med* 11:227–238
- Wu MY, Cao CX, Li Z, Xiao TF (2009) Fatty acids and amino acids in muscle of different breeds of pigs. *J Fujian Agric For Univ* 38(2):166–170 (**in Chinese**)
- Wu C, Liu JF, Kong XF (2012) Effects of dietary arginine and alanine on meat quality, amino acid composition and antioxidant function of Huanjiang Xiang pig. *J Anim Nutr* 3:528–535 (**in Chinese**)
- Yang JJ (2014) Comparison and identification of flavor quality between three kinds of chinese local pork and lean meat pork. Doctorate Degree Thesis, Hefei University of Technology (**in Chinese**)
- Yang GS, Gao GT, Liu YF (1994) Study on the quality of Bamei Pork Fat. *Chin Agric Sci* 27(5):63–68 (**in Chinese**)
- Yang CB, Li AK, Yin YL, Huang RL, Li TJ (2005) Effects of dietary supplementation of cysteamine on growth performance, carcass quality, serum hormones and gastric ulcer in finishing pigs. *J Sci Food Agric* 85(11):1947–1952
- Zhang FJ (2007) Study on the quality characteristics of Gannan Dryopteris hemp Pork. Master thesis of Gansu Agriculture University: 2–10
- Zhang M, Chen ZY, Yuan XP (2011) Research progress in nutrition and meat quality and the detection index and method of meat quality. *Hunan Feed* 1:48–52 (**in Chinese**)
- Zhang S, Chu L, Qiao S, Mao X, Zeng X (2016) Effects of dietary leucine supplementation in low crude protein diets on performance, nitrogen balance, whole-body protein turnover, carcass characteristics and meat quality of finishing pigs. *J Anim Sci* 87(7):911–920
- Zhou XL, Kong XF, Fan JX, Ji YJ, Feng ZM, Yin YL (2014) Effect of monosodium L-glutamate supplementation on carcass character and composition in growing pigs fed a normal or high fat diet. *Sci Technol Food Ind* 35(5):330–337
- Zhu SB, Zhao XT, Zhou CB (2013) Studies on the nutritional composition and flavor substances of pork in Jiang Quhai. *Chin J Anim Husb* 49(15):16–19 (**in Chinese**)