Managing poultry meat quality by nutrition

Berri, C.[1]*, Métayer-Coustard, S.[1], Lessire, M.[1], Bouvarel, I.[2], Duclos, M.[1], Le Bihan-Duval, E.[1], Tesseraud, S.[1]

[1]INRA, UR83 Recherches Avicoles, 37380 Nouzilly, France.
[2]ITAVI, Centre INRA Val de Loire, 37380 Nouzilly, France.
***Corresponding author: berri@tours.inra.fr**

Poultry products are mainly consumed as cut and processed products. Therefore, it is no longer enough for broilers to have high slaughter yields and desirable carcass conformation. Good aesthetic and functional characteristics of the meat must be taken into consideration to satisfy the demands of both processor and consumer. Meat quality is under a complex control including genetics, rearing and slaughter factors. These factors influence the chemical composition of the meat but also the post-mortem muscle metabolism which determine a large number of technological and sensory qualities. This review focuses on the recent advances showing that nutrition can be an effective tool to control muscle development and meat quality in poultry. In particular, the intake of protein, which largely determines muscle growth and yield, may also affect several molecular pathways with significant consequences on muscle post mortem metabolism and meat quality. Indeed, the amino acid supply during the finishing period or just before slaughter can shape the energy reserves of the muscle with a significant impact on meat quality, including colour, processing yield and susceptibility to oxidation. Beyond the control of muscle metabolism, protein intake will also be crucial in controlling the molecular pathways that influence muscle fibre growth and integrity. Thus, recent studies show that in modern heavy strains, improving meat yields by nutrition can also lead to poor meat quality, which results in a lower protein/fat ratio and in the most severe cases in the onset of degenerative defects. Therefore, it is essential to rethink poultry nutrition by taking into account new standards, such as functional, nutritional and storage ability of the meat, but also by developing studies to better understand which molecular pathways can be efficiently modulated by nutrition during animal growth to improve final meat quality.

Keywords: meat quality; pH; muscle growth; nutrition

Introduction

The poultry meat consumption is growing worldwide. In developed countries, meat production is mainly dedicated to cuts and further processed products, which requires specific quality traits related to meat aspect and texture but also storage and processing ability. Most of these characters are under genetic control (Le Bihan-Duval *et al.*, 2008) and are tightly related to muscle energy metabolism. In particular, the ability of the animal to store glycogen in muscle will determine the glycolysis extent post-mortem and the ultimate pH (pHu) value of the meat. In chicken, the pHu is the main determinant of functional and sensorial properties of breast meat, as it influences colour before cooking, drip loss during storage, cooking loss, shear force of cooked meat, and yield after curing-cooking (Alnahhas *et al.*, 2014). Broiler breast meat with high pHu has also been recently associated with myodegenerative defects (white striping, wooden breast) in which the muscle integrity is affected (Petracci *et al.*, 2013; Mudalal *et al.*, 2015). Therefore, controlling breast meat pHu appears as a main goal to achieve in order to decrease the high variability of breast meat quality that is often observed in slaughter plants (Petracci *et al.*, 2009). In addition to genetics, there are many rearing and slaughter conditions that can affect meat pH and quality. Some of them are likely to alter animal energy status with consequences on muscle post-mortem metabolism. This is the case for stress and bird activity before slaughter that alter post-mortem rate of glycolysis (Chabault *et al.*, 2012) or nutrition during the final phase of rearing that can modify bird intermediate metabolism and the energy amount stored in muscle cells (Berri *et al.*, 2014). The purpose of this review is to make an inventory of knowledge's on the impact of nutrition on poultry meat properties and to propose new feeding strategies allowing a joint optimization of performances and product quality.

Changing finishing protein and amino acid intake can modulate energy storage in muscle and meat quality in broiler

Growing animal are using nutrients for growth (protein accretion) and energy storage as lipid or carbohydrate. The balance between protein accretion and energy storage depends on animal needs and nutritional value of their diet. The effect of diet has been mainly studied in relation with body fatness and with muscle yield and lipid composition. Only few studies evaluated the impact of diet on muscle glycogen content. Nevertheless, the muscle glycogen content at slaughter is determinant for meat quality through its effect on the meat pHu. The more glycogen level will be high in the muscle at slaughter, the more meat produced will be acid and exhibit poor sensorial and processing quality.

Feeding strategies to modulate meat quality have been first studied in pigs (Apple, 2007 for review). There is little evidence that pork quality (in particular water holding capacity, WHC) is altered by the lysine or protein level (and source), cereal grain, or fat source used in growing-finishing diets. However, feeding low-starch, high-fibre, high-fat, glycogen-reducing diets effectively improves the WHC of pork. Moreover, supplementing alpha-tocopherol or magnesium improved pork WHC.

In chickens, recent research indicates that modifying protein or amino acid intake can influence muscle pHu and related quality traits (colour, WHC, etc.). Indeed, increasing the level of lysine in the diet of broilers (beyond the needs for growth) improved breast meat yield and reduced drip loss during storage by increasing its pHu (Berri *et al.*, 2008). This result was consistent with the general hypothesis that breast muscle hypertrophy in broilers is accompanied by a decrease in glycogen storage (Berri *et al.*, 2007). Breast muscle glycogen content was also decreased and meat pHu was increased when levels of protein and energy intake were simultaneously increased (Zhao *et al.*, 2012). On the other hand, increasing the finishing protein intake (17 to 23%) without modifying the energy level of the diet resulted in increased muscle glycogen storage, decreased pHu, and impaired colour and WHC (Jlali *et al.*, 2012). However the impact of protein intake on breast meat characteristics may depend on the genetic type, broilers that are more prone to fattening being less sensitive to dietary variations than leaner broilers (Jlali *et al.*, 2012). In general, the impact of protein intake on meat pH and quality is variable and probably dependent on many factors related either to animal or diet characteristics (Yalcin *et al.*, 2010; Lilly et al, 2011; Zhao *et al.*, 2012).

In addition to the amount of protein, the amino acid profile of the diet can affect the pHu of the meat and certain associated traits (colour, WHC). This was shown in a study initially designed to estimate the response of broilers to amino acids during the finishing period by varying levels of digestible lysine (0.7, 0.85, 1.0, and 1.15%) and essential amino acids (90, 100 and 110% of ideal protein described by Mack *et al.*, 1999) at constant energy levels (Lessire *et al.*, 2013). The results showed that deficiency of amino acid provision (-10%) combined with a reduced lysine content (0.7%) favoured the production of meat with high pHu (> 6.0), while the most acid meat (< 5.85) was produced with excess provision of amino acids (+10%) combined with a low lysine intake (0.7%). The pH variations between diets had significant effects on colour and drip loss during storage.

All the studies presented above have considered long-term feeding strategies which also significantly affect broiler growth performance and body composition. However, one study on intermittent feeding suggested that a daily-switch in dietary protein to energy ratio may affect the breast muscle glycogen content from day to day (Mameri *et al.*, 2010), probably with a limited impact on bird growth. We evaluated the possibility of improving the quality of breast meat without impairing broiler growth performance and body composition by distributing diets varying in amino acid content but not energy intake over a very short period (3 days) before slaughter (Guardia *et al.*, 2014). The experimental diets consisted of a control diet with sufficient amounts of amino acids including lysine (1.0%), three lysine-deficient (0.8%) and three lysine-rich (1.2%) diets each with a sufficient, a low (-10%) or a high (+10%) amount of other essential amino acids calculated in proportion to lysine. As in the long-term study (Lessire *et al.*, 2013), lower pHu values were recorded in broilers fed lysine-deficient diets containing high (+10%) amounts of other AA than in broilers fed diets containing low (-10%) or sufficient amounts of other amino acids. Compared to the long-term study cited above, changes in pHu caused by variations in dietary amino acid profiles were fairly moderate. However they significantly affected breast meat lightness that is itself strongly correlated with WHC of meat and therefore processing yield (Qiao *et al.*, 2002; Petracci *et al.*, 2004; Zhuang and Savage, 2010).

Given the extremely close relationship between meat pHu and muscle glycogen at death, it is likely that the changes in pH induced by variations in the intake of amino acids occur through modulation of muscle energy reserves. The hypothesis is that a chicken subjected to amino acid provision in excess of its needs for protein synthesis and muscle growth uses part of its nutrient intake for energy storage, such as glycogen in muscle, thus explaining the decrease in pHu observed. On the other hand, reducing the intake of amino acids may limit the ability to store glycogen in muscle and explain the high pH levels observed in these conditions.

Limiting oxidation by nutrition can improve the storage and processing ability of meat

Improving poultry meat quality can be achieved by increasing oxidative stability during storage and further processing. Oxidative stress, which occurs when the formation of oxidants exceeds the ability of antioxidant systems to remove the reactive oxygen species (ROS), can provoke modifications of lipids and proteins that can change their physical and chemical properties. These modifications can be involved in the regulation of fresh meat quality and also influence the processing properties of meat products. It is known that oxidative stability of poultry meat can be improved by dietary strategies. These strategies, recently reviewed in Estevez (2015), involve reducing the concentration of polyunsaturated lipids in poultry tissues by modifying the lipid composition of the feeds and the supplementation with α-tocopherol and ascorbate alone or in combination with other elements with antioxidant potential, such as selenium, magnesium, and zinc. Dietary strategies based on phenolic-rich plant materials have also been found to be effective against lipid and protein oxidation in various poultry meat and processed poultry products. This includes tea catechins, grape pomace, camelina meal, tomato extract, pea seeds, ginger root, purple coneflower, rosehips, and rosemary leaves.

According the methionine source provided in the diet (DL-methionine, DLM or hydroxy analogue of methionine, DL-HMTBA), the oxidative stress and lipid peroxidation will be more or less marked (Martin-Venegas *et al.*, 2006, Swennen *et al.*, 2011, Willemsen *et al*., 2011). Indeed, fully or partly replacing DLM by its hydroxyl-analog HMTBA was efficient to reduce breast meat susceptibility to oxidation (leg and breast meat) and also increased its pHu, with positive consequences on storage and processing ability (Mercier *et al.*, 2009).

Several factors related to animal or its finishing diet play a role in the occurrence and severity of oxidation process. For instance, oxidation is favored in heavy male turkeys whose daily average gain and fattening during the finishing period are increased (Bourin *et al.*, 2015). Such conditions promote the production of meat containing high haem iron content and low pHu, two factors promoting oxidation process post-mortem. These conditions have been related to low dietary protein/energy ratio during the finishing period, highlighting the importance to rethink animal finishing diet to limit the occurrence of meat quality defects related to low pH or chemical status promoting oxidation post-mortem.

Molecular mechanisms involved in muscle metabolism and meat quality changes related to animal nutrition

As in mammals, the AMP-activated protein kinase (AMPK) complex is a key regulator of the glycogen turn-over in muscle. It also affects its post-mortem depletion in relation to the animal energy status and muscle activity. In broiler breast muscle, differences in muscle glycogen content and pHu have been shown to correspond to difference in AMPK activation (measured through its phosphorylation status), suggesting a role of this cell energy sensor in determining poultry meat quality traits (Sibut *et al.*, 2008). Later on, it was shown that the activation of AMPK complex can be modulated by the diet with consequences on muscle glycogen content. Indeed, a limited protein intake in the finishing diet (17% vs. 23%) resulted in high phosphorylation of the AMPK, reduced glycogen content and improvement of meat color and WHC (Jlali *et al.*, 2012). The use of a 48 h cycle sequential feeding varying in both protein and energy contents also induced changes in AMPK phosphorylation status concomitant to changes in breast muscle glycogen content (Mameri *et al.*, 2010). This indicates that muscle energy metabolism can be modulated on a short-term basis and reinforces our previous hypothesis that pre-slaughter nutrition can efficiently impact meat quality.

A recent study investigated the molecular regulation underlying the control of muscle growth related to protein intake of the diet (Berri *et al.*, 2015). It focused on a population of 36-day-old heavy broilers fed with two different levels of dietary proteins and that showed variable growth performance and breast meat yield. Results showed that the inherent capacity of protein synthesis, estimated by the ratio RNA/protein (also referred as ribosomal capacity), was positively related to growth capacity of animals. Similarly, there was a positive relationship between body weight and muscle expression of the growth factor IGF-1. However, increasing body weight and breast meat yield was inversely related to muscle protein content. Moreover, the breast muscle yield was negatively correlated with markers of mRNA translation into proteins and instead positively with markers of proteolysis. This suggests that in animals that had the highest growth and breast meat yield, stimulation of protein synthesis is impaired and on the contrary proteolysis is increased in the muscle, which may partly explain its lower protein contents. Altogether our observations can be related to the fact that over a certain limit, increased growth rate and live weight can lead to the occurrence of severe breast muscle abnormalities, such as white striping or wooden breast, in which muscle deposition tends to shift from protein to fat and fibrous tissue (Mudalal *et al.*, 2014).

In general, understanding of the molecular pathways that control the quality of the meat is essential for an integrated management of the latter. For this purpose, the study of ‘nutrigenetic’ models can help to unravel the mechanisms and to propose breeding and nutritional strategies that fit both to specific characteristics of the animals and to production objectives. One example is the control of the xanthophyll pigment content of the broiler meat that directly influences its coloration. In chickens, two fully-linked single nucleotide polymorphisms (SNP) located within the promoter of BCMO1 (encoding the β-carotene 15, 15′-monooxygenase that converts β-carotene into colourless retinal) were identified as the most likely causal mutations that explain the variation in yellow colour and in lutein and zeaxanthin pigments content of the breast meat (Le Bihan-Duval et al., 2011). Thanks to a fast genetic test developed for the screening of the two SNPs within a population, we showed that the mutations in BCMO1 could alter the efficacy to metabolize dietary carotenoids and impact bird growth, body composition and meat quality (Jlali et al., 2014). As illustrated by these results on a single gene, birds’ response to feeding can be dependent on its genetics. Thus, understanding the genetic control of meat quality could help to adapt animal nutrition accordingly and prevent meat defects.

How could early nutrition contribute to meat quality?

After-hatch, muscle growth is mainly achieved by cell hypertrophy, i.e, increase in diameter and length of muscle fibers. Moreover, the weight and yield of muscles are closely related to the size of fibers, especially their diameter (Berri *et al.*, 2007). This last decade, progress in genetics and nutrition have dramatically increase breast meat yield and current broiler strains are characterized by very high muscle fiber diameter (Berri *et al.*, 2014). In the same time, myodegenerative defects, such as white striping and wooden breast, have appeared that are clearly related to animal growth rate and muscle yield (Kuttapan *et al.*, 2012, 2013; Sihvo *et al.*, 2014; Mudalal *et al.*, 2015). So far, no study has shown any impact of nutrition on the occurrence of these defects, although it is suspected that diet optimizing the genetic potential of animals is an additional risk factor. However, if we assume that the very high muscle fiber diameter can be the cause of muscle integrity problems, it would be appropriate to find early nutritional solutions to hasten muscle fiber proliferation and obtain muscles with smaller but more numerous fibers.

Several studies demonstrate that the timing of early post hatch feed restrictions to chicks is critical for the early and late development of the Pectoralis major muscle (Halevy *et al.*, 2000; Bigot *et al.*, 2003). It decreases satellite cell proliferation and alter the expression pattern of genes required for muscle satellite cell proliferation and differentiation (Halevy *et al.*, 2000; Velleman *et al.*, 2014). More precisely, the expression of MyoD and MRF4 (proliferation markers) was significantly increased by feed restriction during the first week post hatch, while the expression of myogenin (that is required for differentiation) was significantly decreased. In the same way, the improvement of vitamin D status by replacing the majority of D3 in the diet with 25OHD3 stimulated the early expression of MyoD and Pax7 and delayed the transition between embryonic and neonatal myosin heavy chain isoforms in the skeletal muscle of 7-day-old chicks (Berri *et al.*, 2013). Even if the consequences on muscle properties of such changes is still unknown, it is interesting to note that breast meat from birds fed 25OHD3 contained more protein and less fat and water than those fed D3 (Petracci and Sirri, not published). Myoblast proliferation can also be promoted by *in ovo* feeding with long-term consequences on muscle weight and yield (Kornasio *et al.*, 2011). Taken together, these studies highlighted the importance of considering early chick nutrition as a tool to control morphological development of the breast muscle in poultry in order to limit the occurrence of muscle abnormalities or myopathies due to intense genetic selection on growth rate and breast meat yield.

Conclusions

Even if the meat quality has become a crucial issue for the poultry meat industry, it is still poorly controlled. The reasons are many but include the rather low interest of breeders and nutritionists for years and the multitude of variation factors involved. However, serious quality defects that are currently observed in slaughterhouses have sparked a renewed interest for the quality of poultry meat. If it is known that the structural and metabolic abnormalities within muscles are a direct consequence of the intensive selection for growth and meat yield, it is also very important to know the role of diet on the emergence of these defects. Indeed, in most cases the defects observed involve metabolic dysfunction and, in the most severe cases, cell degeneration associated with muscle fiber hypertrophy. So better control the muscle growth and improve its energy metabolism and integrity may go through a change of food programs, including during the early periods of myogenesis. Such improvements, however, will require further research to understand the biological basis of meat quality and the role of nutrients in the control of muscle development, and to implement appropriate nutritional strategies to reduce the incidence of meat quality defects in poultry.

Acknowledgements

Some of the studies presented as examples in this review received financial support from INRA, French Minister of Agriculture and professionals of animal feed industry (Adisseo, Ajinomoto Eurolysine, CCPA, DSM).

References

APPLE J.K. (2007) Effects of nutritional modifications on the water-holding capacity of fresh pork: a review. Journal of Animal Breeding and Genetics 2007 **124 Suppl** 1:43-58.

ALNAHHAS, N., BERRI, C., BOULAY, M., BAEZA, E., JEGO, Y., BAUMARD, Y., CHABAULT, M. and LE BIHAN-DUVAL, E. (2014) Selecting broiler chickens for ultimate pH of breast muscle: analysis of divergent selection experiment and phenotypic consequences on meat quality, growth, and body composition traits. *Journal of Animal Science* **92:** 3816-3824.

BERRI, C., BAEZA, E., METAYER-COUSTARD, S., LESSIRE, M., BOUVAREL, I., DUCLOS, M., TESSERAUD, S., LE BIHAN-DUVAL, E. (2014). Genetic and nutritional strategies to control glycogen metabolism and meat quality in chickens. In *14th European Poultry Conference, Stavanger (NOR), 2014/06/23-27* pp 339-351.

BERRI, C., BESNARD, J. and RELANDEAU, C. (2008) Increasing dietary lysine increases final pH and decreases drip loss of broiler breast meat. *Poultry Science* **87:** 480-484.

BERRI, C., CAILLEAU-AUDOUIN, E., CROCHET, S., BORDEAU, T., PANHÉLEUX, M., BÉBIN, K., TESSERAUD, S. (2015) Molecular regulation underlying the control of body weight and breast meat yield in broiler. In *22th European Symposium on the Quality of Poultry Meat, Nantes (FRA) 2015/05/10-13.*

BERRI, C., LE BIHAN-DUVAL, E., DEBUT, M., SANTE-LHOUTELIER, V., BAEZA, E., GIGAUD, V., JEGO, Y. and DUCLOS, M.J. (2007) Consequence of muscle hypertrophy on characteristics of pectoralis major muscle and breast meat quality of broiler chickens. *Journal of Animal Science* **85:** 2005-2011.

BERRI, C., PRAUD, C., GODET, E., DUCLOS, M.J. (2013). Effect of dietary 25-hydroxycholecalciferol on muscle tissue and primary cell culture properties in broiler chicken. In: Book of Abstracts (p. 6 p.). In *21th European Symposium on the Quality of Poultry Meat, Bergamo, (ITA) 2013-09-15-19). World's Poultry Science Journal* **69** supplement.

BIGOT, K., TAOUIS, M., PICARD, M. and TESSERAUD, S. (2003) Early post-hatching starvation delays p70 S6 kinase activation in the muscle of neonatal chicks. *British Journal of Nutrition* **90:** 1023-1029.

BOURIN, M., BAÉZA, E., MIKA, A., GODET, E., CHARTRIN, P., SANTÉ-LHOUTELLIER, V., BERRI, C. (2015) What are the rearing factors that favor oxidation of turkey meat? In *22th European Symposium on the Quality of Poultry Meat, Nantes (FRA) 2015/05/10-13.*

CHABAULT, M., BAÉZA, E., GIGAUD, V., CHARTRIN, P., CHAPUIS, H., BOULAY, M., ARNOULD, C., D'ABBADIE, F., BERRI, C. and LE BIHAN-DUVAL, E. (2012) Analysis of a slow-growing line reveals wide genetic variability of carcass and meat quality-related traits. *BMC Genetics* **13:** 90.

ESTÉVEZ, M. (2015) Oxidative damage to poultry: from farm to fork. *Poultry Science*, in press.

GUARDIA, S., LESSIRE, M., CORNIAUX, A., MÉTAYER-COUSTARD, S., MERCERAND, F., TESSERAUD, S., BOUVAREL, I., and BERRI, C. (2014) Short-term nutritional strategies before slaughter are effective in modulating the final pH and color of broiler breast meat. *Poultry Science* **93:** 1764-1773

HALEVY, O., GEYRA, A., BARAK, M., UNI, Z. and SKLAN, D. (2000) Early posthatch starvation decreases satellite cell proliferation and skeletal muscle growth in chicks. *Journal of Nutrition* **130:** 858-864.

JLALI, M., GIGAUD, V., MÉTAYER-COUSTARD, S., SELLIER, N., TESSERAUD, S., LE BIHAN-DUVAL, E. and BERRI, C. (2012) Modulation of glycogen and breast meat processing ability by nutrition in chickens: Effect of crude protein level in 2 chicken genotypes. *Journal of Animal Science* **90:** 447-455.

JLALI, M., GRAULET, B., CHAUVEAU-DURIOT, B., GODET, E., PRAUD, C., SIMOES NUNES, C., LE BIHAN-DUVAL, E., BERRI, C., DUCLOS, M. (2014) Nutrigenetics of carotenoid metabolism in the chicken: a polymorphism at the β, β-carotene 15,15'-mono-oxygenase 1 (BCMO1) locus affects the response to dietary β-carotene. *British Journal of Nutrition* **111:** 2079-2088.

KORNASIO, R., HALEVY, O., KEDAR, O. and UNI, Z. (2011) Effect of *in ovo* feeding and its interaction with timing of first feed on glycogen reserves, muscle growth, and body weight. *Poultry Science* **90:** 1467-1477.

KUTTAPPAN, V.A., BREWER, V.B., APPLE, J.K., WALDROUP, P.W. and OWENS, C.M. (2012) Influence of growth rate on the occurrence of white striping in broiler breast fillets. *Poultry Science* **91:** 2677-2685.

KUTTAPPAN VA, BREWER VB, MAUROMOUSTAKOS A, MCKEE SR, EMMERT JL, MEULLENET JF, OWENS CM. (2013) Estimation of factors associated with the occurrence of white striping in broiler breast fillets. Poultry Science **92:** 811-819.

LE BIHAN-DUVAL, E., DEBUT, M., BERRI, C., SELLIER, N., SANTE-LHOUTELLIER, V., JEGO, Y. and BEAUMONT, C. (2008) Chicken meat quality: Genetic variability and relationship with growth and muscle characteristics. *BMC Genetics* **9:** 53.

LE BIHAN-DUVAL, E., NADAF, J., BERRI, C., PITEL, F., GRAULET, B., GODET, E., LEROUX, S., DEMEURE, O., LAGARRIGUE, S., DUBY, C., COGBURN, L. A., BEAUMONT, C., DUCLOS, M. (2011) Detection of a Cis eQTL controlling BMCO1 gene expression leads to the identification of a QTG for chicken breast meat color. *Plos One* **6 (7):** e14825.

LESSIRE, M., PRIMOT, Y., CORRENT, E., FRAYSSE, P., TESSERAUD, S. and BERRI, C. (2013) Lysine supply in finishing broilers: effect on performances and meat quality. In *4th International Symposium on Energy and Protein Metabolism and Nutrition, Sacramento (USA), 2013/09/09-12* **134:** 209-210.

LILLY, R.A., SCHILLING, M.W., SILVA, J.L., MARTIN, J.M. and CORZO, A. (2011) The effects of dietary amino acid density in broiler feed on carcass characteristics and meat quality. *Journal of Applied Poultry Research* **20:** 56-67.

MACK, S., BERCOVICI, D., DE GROOTE, G., LECLERCQ, B., LIPPENS, M., PACK, M., SCHUTTE, J.B. and VAN CAUWENBERGHE, S. (1999) Ideal amino acid profile and dietary lysine specification for broiler chickens of 20 to 40 days of age. *British Poultry Science* **40:** 257-265.

MAMERI, H., DUPONT, J., JOUBERT, R., COLLIN, A., CROCHET, S., CAILLEAU-AUDOUIN, E., TESSERAUD, S. and MÉTAYER-COUSTARD, S. (2010) Mechanisms regulating the peripheral utilisation of glucose: involvement of AMPK. In *proceedings of the 3rd EAAP ISEP* **127:** 259-260.

MARTIN-VENEGAS, R., GERAERT, P.A. and FERRER, R. (2006) Conversion of the Methionine Hydroxy Analogue, DL-2-Hydroxy-(4-Methylthio) butanoic Acid, to Sulfur-Containing Amino Acids in the Chicken Small Intestine. *Poultry Science* **85:** 1932-1938.

MERCIER, Y., BERRI, C., BAÉZA, E., BORDEAU, T., CHARTRIN P., MERCERAND, F. and GERAERT, P.A. (2009) Improvement of muscle oxidative stability and processing yield in relation with dietary methionine sources. In *Poultry Science Association 98th Annual meeting. Raleigh, North Carolina (USA) 2009/07/20-23*. Abstract 117

MUDALAL, S., BABINI, E., CAVANI, C. and PETRACCI, M. (2014) Quantity and functionality of protein fractions in chicken breast fillets affected by white striping. *Poultry Science* **93:** 2108-2116.

MUDALAL, S., LORENZI, M., SOGLIA, F., CAVANI, C. and PETRACCI, M. (2015) Implications of white striping and wooden breast abnormalities on quality traits of raw and marinated chicken meat. *Animal* **9:** 728-734.

PETRACCI, M., BETTI, M., BIANCHI, M. and CAVANI, C. (2004) Color variation and characterization of broiler breast meat during processing in Italy. *Poultry Science* **83:** 2086-2092.

PETRACCI, M, BIANCHI, M, CAVANI, C. (2009) The European perspective on pale, soft, exudative conditions in poultry. *Poultry Science* **88:** 1518-1523.

PETRACCI, M, MUDALAL, S, BONFIGLIO, A and CAVANI, C. (2013) Occurrence of white striping under commercial conditions and its impact on breast meat quality in broiler chickens. *Poultry Science* **92:** 1670-1675

QIAO, M., FLETCHER, D.L., SMITH , D.P. and NORTHCUTT, J.K. (2002) Effects of raw broiler breast meat color variation on marination and cooked meat quality. *Poultry Science* **81:** 276-280.

SIBUT, V., LE BIHAN-DUVAL, E., TESSERAUD, S., GODET, E., BORDEAU, T., CAILLEAU-AUDOUIN, E., CHARTRIN, P., DUCLOS, M. J. and BERRI, C. (2008) Adenosine monophosphate-activated protein kinase involved in variations of muscle glycogen and breast meat quality between lean and fat chickens. *Journal of Animal Science* **86:** 2888-2896.

SIHVO, H.K., IMMONEN, K. and PUOLANNE, E. (2014) Myodegeneration with fibrosis and regeneration in the pectoralis major muscle of broilers. Veterinary Pathology **51:** 619-623.

SWENNEN, Q., GERAERT, P.A., MERCIER, Y., EVERAERT, N., STINCKENS, A., WILLEMSEN, H., LI, Y., DECUYPERE, E. and BUYSE, J. (2011) Effects of dietary protein content and 2-hydroxy- 4-methylthiobutanoic acid or dl-methionine supplementation on performance and oxidative status of broiler chickens. *British Journal of Nutrition* **21:** 1-10.

VELLEMAN, S.G., COY, C.S. and EMMERSON D.A. (2014) Effect of the timing of posthatch feed restrictions on the deposition of fat during broiler breast muscle development. *Poultry Science* 93: 2622-2627.

WILLEMSEN, H., SWENNEN, Q., EVERAERT, N., GERAERT, P.A., MERCIER, Y., STINCKENS, A., DECUYPERE, E. and BUYSE, J. (2011) Effects of dietary supplementation of methionine and its hydroxy analog DL-2-hydroxy-4-methylthiobutanoic acid on growth performance, plasma hormone levels, and the redox status of broiler chickens exposed to high temperatures. *Poultry Science* 90: 2311-2320.

YALÇIN, S., ÖZKUL, H., ÖZKAN, S., GOUS, R., YAŞA, I. and BABACANOĞLU, E. (2010) Effect of dietary protein regime on meat quality traits and carcase nutrient content of broilers from two commercial genotypes. *British Poultry Science* **51:** 621-628.

ZHAO, J.P., ZHAO, G.P., JIANG, R.R., ZHENG, M.Q., CHEN, J.L., LIU, R.R. and WEN, J. (2012) Effects of diet-induced differences in growth rate on metabolic, histological, and meat-quality properties of 2 muscles in male chickens of 2 distinct broiler breeds. *Poultry Science* **91:** 237-247.

ZHUANG, H., and SAVAGE, E.M. 2010. Comparisons of sensory descriptive flavor and texture profiles of cooked broiler breast fillets categorized by raw meat color lightness values. *Poultry Science* **89:** 1049-1055.