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Meat quality in fast-growing broiler chickens

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During the past few decades there has been a notable increase in the demand for poultry meat due to its low cost, good nutritional profile and suitability for further processing. Moreover, current forecasts and projection studies have predicted that the expansion of the poultry market will continue in the future. This growing demand has led to progressive improvements in genetic selection to produce fast-growing broilers, inducing the appearance of several spontaneous, idiopathic muscle abnormalities along with an increased susceptibility to stress-induced myopathy. Such muscle abnormalities have several implications for the quality of fresh and processed products, as breast meat that is affected by deep pectoral myopathy is usually rejected due to its unacceptable appearance. In addition, pale, soft and exudative like meat has a low processing ability due to its reduced water holding capacity, soft texture and pale colour. Finally, the high incidence of abnormalities observed in chicken breast muscles such as white striping (characterised by superficial white striations) and wooden breast (characterised by pale and bulging areas of substantial hardness) impair both the appearance and technological traits of breast meat. This review evaluates the consequences of genetic selection on muscle traits and describes the relevance of major breast abnormalities on nutritional, technological, sensorial and microbial characteristics of raw and processed meat.

Keywords: broiler; genetics; meat; abnormalities; sensory quality

Genetic improvements and breast meat abnormalities

Selection criteria of broiler chickens has been adapted through the decades according to the evolution of the market demand for chicken meat and increased population growth (*Table 1*). As one example, before World War II poultry were marketed as live birds, and thus meat-type chickens were basically selected based on the characteristics of live birds. After this period, poultry started to be sold in the form of prepared carcasses in small markets and grocery stores in towns and cities, leading to an economic interest in selecting animals according to carcass yield. About 40 years ago, market demand towards cut-up portions increased and birds were selected according to main carcass part yields, such as breast and

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legs. Finally, during the last two decades, the increasing demand for further-processed products, coupled with a preference for breast meat in Western countries, has shifted selection towards birds with high breast development (Fletcher, 2004).

Table 1 Relationships between the evolution of marketing forms, selection criteria of chicken broilers and appearance of breast meat abnormalities.

Item	Year 1940	1960	1980	1995	2010
Main form of commercialisation	- live bird	- whole carcass	- cut-up	- cut-up - processed products	- cut-up - processed products
Main selection criteria	- live performances	- live performances - carcass yield	- live performances - carcass yield - cut-up yield	- live - performances - carcass yield - cut-up yield - meat yield	- live performances - carcass yield cut-up yield - meat yield
Meat quality abnormalities			- deep pectoral disease	- deep pectoral disease - PSE-like	- deep pectoral disease - PSE-like - white striping - wooden breast

Reasons for the increasing demand of chicken breast meat are attributed to its healthy nutritional profile, sensory properties that make breast meat very flexible for any type of home-cooking style as well as for manufacturing processed products. Additionally, mild flavour and the high tenderness of breast meat allow imparting a wide range of desired flavour profiles and textures of processed meat products that meet market needs by targeting different groups of consumers. Finally, breast meat is very suitable for quick and easy home-cooking, which is very important in modern societies where people tend to spend increasingly less time on preparation of meals at home (Petracci *et al.*, 2013a). As a consequence, the poultry industry has been pushed to increase breast yield and to produce heavier birds for further processing (Brewer *et al.*, 2012). However, it also has to deal with meat quality issues that were not serious or significant when most poultry was sold as whole birds (Barbut *et al.*, 2008).

Consequently, the substantial genetic progress made in the last 50 years has resulted in reduction of the growing time by about one-half (to 40 days or less) to obtain a market weight bird (about 2 kg) (Havenstein *et al.*, 2003a; Aviagen, 2007; 2012). Moreover, in the last 10 years breast meat yield has increased by 5%, and currently exceeds one fifth of the weight of the bird (Aviagen, 2012) (*Table 2*).

Table 2 Progress in breast weight and yield in commercial broiler hybrids from 1957 to 2012.

Year	Hybrid	Body weight (g)	Age (d)	Breast weight[3] (g)	Breast yield (%)
1957[1]	Athens-Canadian random bred	2,078	57	280	13.5
2001[1]	Ross 308	2,207	43	349	15.8
2007[2]	Ross 308	2,200	36	410	18.6
2012[2]	Ross 308	2,200	35	464	21.1

[1]Havenstein *et al.* (2003b); [2]Aviagen (2007; 2012); [3]breast muscles without bone and skin.

This substantial improvement has been achieved by increasing the growth rate of breast muscles by inducing hypertrophy in existing fibres, and, to a lesser extent, by hyperplasia because the total number of fibres is generally fixed after hatching. On the another hand, selected modern hybrids show a higher density of fast-twitch fibres that are characterised by a higher diameter and a lower rate of protein degradation compared with unselected birds (Mahon, 1999; Schreurs, 2000; Picard *et al.*, 2002; Scheuermann *et al.*, 2004; Branciari *et al.*, 2009). Indeed, an increase in fibre size is associated with lower capillarisation that may lead, under certain conditions, to an inadequate supply of oxygen and nutrients to muscle cells. In addition, it may be associated with inadequate elimination of metabolic intermediate products that can compromise fibre functionality and result in homeostatic dysregulation. In particular, an increase in the concentration of calcium may activate some proteolytic and lipolytic enzymes leading to membrane dysfunction and increased plasma concentration of enzymes such as creatine kinase and lactate dehydrogenase (Mitchell, 1999; Sandercock and Mitchell, 2003; MacRae *et al.*, 2006).

As a consequence, selection towards increased growth rate and breast-yield over the last 30 years has increased the incidence of breast meat abnormalities such as deep pectoral myopathy (DPM) and pale-soft-and-exudative (PSE)-like meat, and more recently white-striping and wooden-breast (*Table 2*). DPM was firstly recognised in chicken breeders, but it also appeared in fast-growing birds about 30 years ago (Siller, 1985). Despite the efforts exerted by poultry breeders and producers to reduce its occurrence, DPM remains a significant quality issue in poultry processing plants. *Pectoralis minor* muscles affected by DPM are trimmed during processing causing downgrading of breast meat and subsequent economic loss for the poultry industry, while the quality of the remainder of the breast is not affected and acceptable for human consumption (Kijowski *et al.*, 2014). On the other hand, the occurrence of the PSE-like condition in poultry had been mentioned some decades ago (Solomon *et al.*, 1998; Mitchell, 1999). Similarly to DPM, despite advances in knowledge, there is still a significant proportion of breast meat with PSE-like characteristics. The PSE-like condition not only impairs appearance, but reduces the ability of meat to hold and bind water during processing and storage (Duclos *et al.*, 2007; Barbut *et al.*, 2008; Petracci and Cavani, 2012). These abnormalities have been intensively studied by several researchers, and their aetiology are well known. Hence, to a certain extent the poultry industry can manage the adverse impact of these abnormalities during production and processing. Recently, new muscle abnormalities such as 'white striping' and 'wooden' meat have emerged. This review briefly discusses the most recent studies that describe the adverse impacts of the PSE-like condition on the quality of breast meat and provides details on the implications of such problems on the meat poultry industry.

Breast muscle abnormalities with relevance to meat quality

PSE-LIKE CONDITIONS

PSE-like breast meat is usually downgraded in retail marketing due to the presence of drip and differences in colour. Separating PSE-like meat from normal meat is relatively difficult since the identification of colour-related problems are problematic (Fletcher, 2002). The causes of PSE meat in broilers have been well clarified over the last 20 years (Solomon *et al.*, 1998; Mitchell, 1999; Barbut *et al.*, 2008; Petracci *et al.*, 2009). Under normal conditions, breast muscles have a pH> 7 before slaughter, while the pH decreases to 5.8−5.9 after 6 hours *post-mortem*. However, there are two types of anomalous onset of PSE: i) fast-acidifying meat, in which the pH drops below 6 within 1 hour *post-mortem*, similar to what occurs in PSE pork meat (*Figure 1b*) or ii) the rate of acidification is more or less the same, but the final pH is lower than normal (<5.8), an abnormality termed as 'acid meat' (*Figure 1a*). In both cases, meat is a paler colour and has reduced water holding capacity. Le-Bihan *et al.* (2008) demonstrated that there was little genetic relationship between the pH measured immediately after the death of birds and at the end of the *post-mortem* acidification process. This seems to indicate that the two mechanisms are likely to be independent.

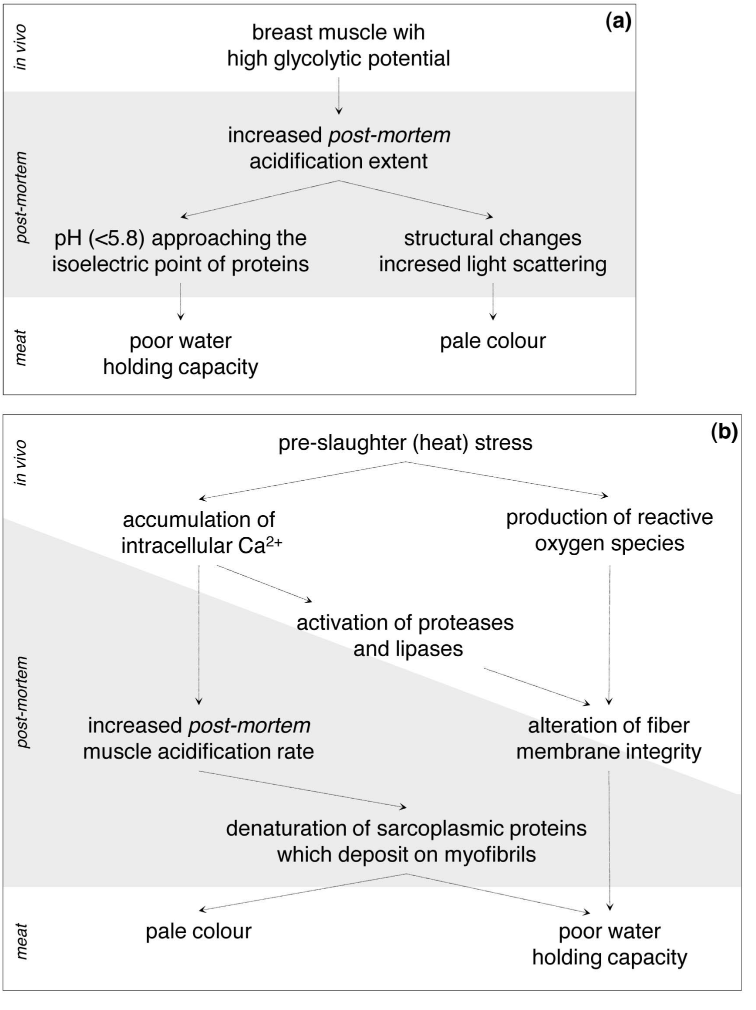

Figure 1 Mechanisms of appearance of PSE-like breast meat in broilers. a) Acid meat; b) Fast acidifying meat.

Fast growing or heavier birds have been shown to be more susceptible to heat stress because of their reduced thermoregulatory capacity compared with their genetic predecessors (Sandercock *et al.*, 2006). Therefore, exposure of birds to high temperatures during preslaughter phases may exacerbate negative effects (Petracci *et* *al.*, 2010). Sandercock *et al.* (2009) suggested that genetic selection for increased growth rate and breast yield altered cation regulation in the muscle cells of modern chicken hybrids. Increased intracellular calcium and free radical production in muscle can alter membrane integrity and increase the rate of muscle acidification during *post-mortem* times at high temperature (Sandercock *et al.*, 2001; 2009). These conditions may induce denaturation of sarcoplasmic proteins and alter membrane integrity that reduce the water holding ability and result in a lighter colour of meat (Van Laack *et al.*, 2000) (*Figure 1b*).

However, PSE meat can originate from birds with a high glycolytic potential (acid meat) (*Figure 1a*) (Berri *et al.*, 2005). After slaughter, the high glycogen content causes a lower ultimate pH that is close to the isoelectric point of myofibrillar proteins. At the isoelectric point, meat has a low ability to retain liquids and is a paler colour (Barbut, 2002). At a genetic level, the correlation between breast muscle glycolytic potential and ultimate pH is close to -1 (Le Bihan-Duval *et al.*, 2008; Alnahhas *et al.*, 2014). In addition, it has been demonstrated that selecting broilers for higher breast meat yield leads to higher ultimate pH (Jlali *et al.*, 2012; Alnahhas *et al.*, 2014). These studies indicated that it is possible to select birds for high breast yield and decrease the incidence of PSE-like meat, without compromising quality traits. However, it should not be forgotten that increasing the ultimate pH may induce the occurrence of dark-firm and dry (DFD) meat with possible detrimental effects on microbial and sensory traits (Barbut *et al.*, 2008).

It has been demonstrated that diet can affect the glycolytic potential of breast muscles and the pH of meat. Guardia *et al.* (2014) studied the impact of inclusion of different dietary levels of lysine and other amino acids on the pH of breast meat and found that lower pH values were observed in broilers fed lysine-deficient diets containing a high amount of other amino acids. Previous studies have demonstrated that lysine supplementation above recommendations promoted protein synthesis and increased breast muscle yield in chickens (Berri *et al.*, 2008). This may limit the use of other amino acids for energy purposes, including storage as muscle glycogen, especially when the amounts of other essential amino acids are low.

WHITE-STRIPING AND WOODEN-BREAST ABNORMALITIES

White striping is described as a manifestation of striations parallel to muscle fibres on the ventral surface of broiler breast fillets (Kuttappan *et al.*, 2009). The aetiological causes of white striping are poorly known, although it has been already established that several farming factors may be involved (*Table 3*).

Table 3 Influence of live broiler production factors on the occurrence of white striping in breast meat.

Live production factors	Mode of action on white striping occurrence	References
genotype	high > standard breast-yield	Petracci *et al.* (2013b) Lorenzi *et al.* (2014)
sex	males > females	Kuttappan *et al.* (2013a) Lorenzi *et al.* (2014)
growth rate	higher > lower	Kuttappan *et al.* (2012a; 2013b) Lorenzi *et al.* (2014)
diet	high > low energy diet	Kuttappan *et al.* (2012a)
slaughtering weight	heavier > lighter	Kuttappan *et al.* (2013a) Lorenzi *et al.* (2014)

More recently, ‘wooden’ breast meat has been observed, whereby the muscles are hard, out bulging, pale and often accompanied with white striping (Sihvo *et al.*, 2014).

Observations showed that histopathological changes in white striped and wooden breast muscles had similar features (Kuttappan *et al.*, 2013b; Sihvo *et al.*, 2014; Ferreira *et al.*, 2014), and thus they may have a common aetiology. Histological observations on white-striped meat indicated an increase in degenerative and atrophic fibres associated with loss of cross striations, variation in fibre size, floccular/vacuolar degeneration and lysis of fibres, mild mineralisation, occasional regeneration (nuclear rowing and multinucleated cells), mononuclear cell infiltration, lipidosis and interstitial inflammation and fibrosis (Kuttappan *et al.*, 2013b). Similar features were found by Ferreira *et al.* (2014), although proliferation of connective tissue was not evident in birds slaughtered at earlier ages. The histological changes in wooden breast meat showed different levels of polyphasic myodegeneration with regeneration accompanied by accumulation of interstitial connective tissue (fibrosis) that is quite similar to what has been observed for white striping (Sihvo *et al.*, 2014). It should be noted that similar lesions have been observed in leg muscles and backs of the carcass (Zimermann *et al.*, 2012; Kuttappan *et al.*, 2013b).

Haematologic and serologic profiles of white-striped meat show the absence of systemic infection or inflammation, although increased levels of creatine kinase indicate muscle damage (Kuttappan *et al.*, 2013c). It can be assumed that the faster growth rate, especially of breast muscle, leads to unsustainable pressure on muscle metabolism which prompts the beginning of degenerative features that are similar to muscular dystrophies such as Duchenne. Additionally, it can be assumed that increased free radical production and accumulation of intracellular calcium may promote alteration of fibre membrane integrity and degradation of proteins due to activation of proteases and lipases. This can lead to fibre necrosis that overtakes the regenerative capacity of muscle (*Figure 2*). Indeed, even though white striping has some similarities to nutritional muscular dystrophy, which is related to vitamin E deficiency, it was found that dietary inclusion of different vitamin E levels had no or little effect on the incidence of white striping (Kuttappan *et al.*, 2012b; Guetchom *et al.*, 2012).

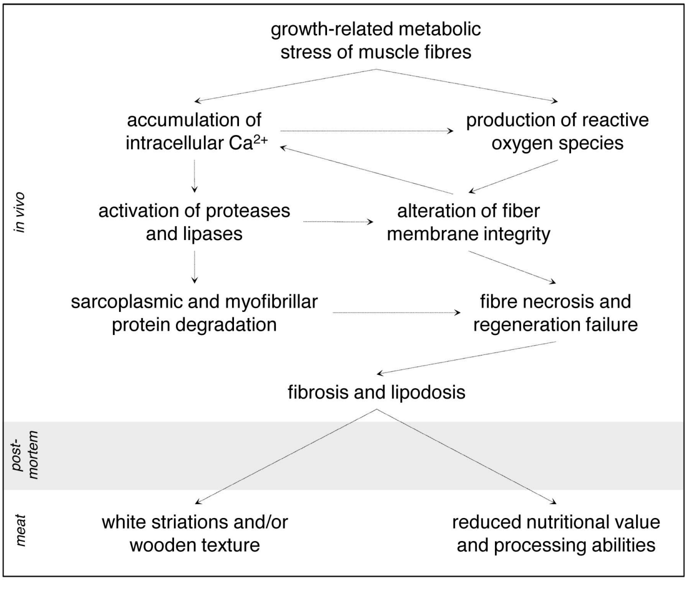

Figure 2 Possible origins of emerging abnormalities (white-striping and wooden breast) of breast meat in broilers.

It has recently been reported that the presence of white striations is associated with modification of meat composition. Indeed, white-striped fillets exhibit a higher percentage of moisture, intramuscular fat and collagen, and lower contents of protein and ash, in comparison with normal fillets (Petracci *et al.*, 2014). In addition, there is a substantial decline in the content and solubility of myofibrillar and sarcoplasmic proteins in white striped breast meat (Mudalal *et al.*, 2014).

Consequences of breast muscle abnormalities on meat quality

NUTRITIONAL VALUE

One of the main reasons driving the success of poultry meat is the perceived healthy nutritional profile compared with pork and beef meat. Indeed, poultry meat, and in particular breast meat, fits the modern consumer demand for low fat, sodium and cholesterol (Cavani *et al.*, 2009). It has recently been observed that chicken meat retains the same nutritional features found in the past (Wang *et al.*, 2010). Whilst PSE has minimal effects on the proximate composition of meat (Qiao *et al.*, 2002), white striping changes the composition of breast meat and may change nutritional value. Kuttappan *et al.* (2012a) found that white-striped fillets had a higher fat content and lower protein content compared with normal fillets. Petracci *et al.* (2014) showed that severe white-striped fillets had a higher total energy content than normal fillets, while the contribution of energy from fat was increased about three-fold. Moreover, breast meat affected by white striping shows an increase in the collagen to total protein ratio, which means that the nutritional value is reduced due to the low digestibility of collagen and deficiency of some essential amino acids (Petracci *et al.*, 2014; Mudalal *et al.*, 2014).

Both moderate and severe white striping are associated with changes in the composition and hence reduced nutritional quality of breast meat. In general, breast meat affected by severe white striping is usually used for manufacturing further processed products (*e.g.* sausages or nuggets) where the chemical composition can be modified during formulation. Fillets with moderate white striped are marketed for fresh retailing, even though cut-up products may have different nutritional characteristics compared with those reported on the label and with consumer expectations towards poultry meat (*e.g.* low calories and fat). This means that the cut-up breasts (whole or sliced) can have somewhat different nutritional characteristics compared with those reported on the label and with consumer expectations towards poultry meat (Petracci *et al.*, 2014).

TECHNOLOGICAL AND SENSORY PROPERTIES

It is well known that PSE is associated with a lower water holding capacity (WHC) and poorer sensory traits of chicken breast meat. WHC is attributed to partial protein denaturation due to the combination of acidic conditions and high muscle temperature in early *post-mortem* muscle (*Figure 1b*). Moreover, a reversible loss of the ability to hold water can be explained by the fact the protein isoelectric point is approached when the pH is lower than 5.8 (*Figure 1a*) (Petracci *et al.*, 2004; Duclos *et al.*, 2007; Barbut *et al.*, 2008). This latter effect can be partially resolved when PSE-like meats are used as raw materials in manufacturing further processed products because the pH can be increased by the inclusion of alkaline agents such as phosphates, bicarbonates and citrates (Petracci *et al.*, 2013a).

The presence of a certain proportion of PSE-like meat can be accepted by poultry plants, especially during the hot season. However, white striping (Kuttappan *et al.*, 2012c) and wooden breast abnormalities impair the visual appearance of breast meat and a consequent reduction of consumer acceptability. Therefore, the poultry industry usually downgrades white striped and wooden breast fillets, especially in severe cases, and allocates them for further processing. In addition, it has been found that these abnormalities are associated with a strong impairment of the technological properties of breast meat (Petracci *et al.*, 2013b; Mudalal *et al.*, 2015). In this context, it has been reported that white-striped meat has a dramatically lower water-holding/binding capacity (marinade uptake, cooking loss, and yield) and a softer texture than normal meat (Petracci *et al.*, 2013b). Similar features were recently observed in wooden breast fillets (Mudalal *et al.*, 2015). From preliminary observations, it appears that wooden breast has an even greater effect on the WHC of meat in comparison with white striped meat (Mudalal *et al.*, 2015). The causes of lower WHC for both types of muscle abnormalities are still not fully understood, but the occurrence of muscle degeneration in both breast meat abnormalities resulted in substantial reduction of muscular contractile and sarcoplasmic proteins (Mudalal *et al.*, 2014). In this context, a recent study evaluated the impact of inclusion of different levels of wooden breast on the quality traits of processed meat products (Puolanne and Ruusunen, 2014). Notwithstanding, this aspect still needs further investigation.

Based on the available data, it can be concluded that these emerging abnormalities not only affect the appearance of fresh product, but also have poor technological properties. Therefore, the effectiveness of further processing strategies to alleviate the extent of these problems is restricted to PSE meat.

MICROBIAL SHELF-LIFE

If high ultimate pH has a positive effect on the water holding capacity and processing characteristics, microbiological stability may be compromised when the ultimate pH exceeds 6 (Barbut *et al.*, 2008). It is well-known that microbial growth depends strongly on the pH of meat. In particular, breast meat characterised by high pH (>6.0) is more likely to become contaminated with microbial growth and can trigger different types of spoilage microorganisms that impair taste, flavour and appearance (Mallia *et al.*, 2000a; 2000b). Therefore, selection programs to improve meat quality must keep the pH level within the upper threshold value to maximise the benefits of PSE-like prevention and minimise the potential for decreased shelf-life, as previously suggested in the pig sector (Barbut *et al.*, 2008). There are no published studies on microbial shelf-life of white-striped and wooden breast fillets, although both are known to be linked to ultimate meat pH and may reduce shelf life due to contamination (Petracci *et al.*, 2013b; Mudalal *et al.*, 2015).

Conclusions

The ever-increasing genetic pressure to improve growth rates and breast yields of broiler chickens has led to a high incidence of several abnormalities in breast muscles during the last 20 years (Petracci *et al.*, 2009; Kijowski *et al.*, 2014; Lorenzi *et al.*, 2014). However, until a few years ago, economic losses due to meat downgrading was largely counterbalanced by gains in the increasingly high growth rates of birds and greater breast meat yields. Nowadays, the occurrence of emerging breast meat abnormalities, such as white striping and wooden breast, is associated with higher percentages of downgrading that are no longer sustainable for the poultry industry. In addition, there is also a decrease in the nutritional, sensory and technology quality of meat that may negatively impact current consumer attitudes towards poultry meat. As a consequence, should the industry consider a step back in the increase in growth rates and breast development in order to reduce the extent of the problem? The answer to this question may differ depending on the geographical market. The most vulnerable markets are those where production systems are more efficient and have higher growth rates, birds are slaughtered at higher slaughter weights/ages and the majority of poultry products are sold as whole carcasses and pieces. In such developed poultry markets, increasing the occurrence of myopathies may negatively affect consumer attitudes toward perceived animal welfare. Greater specialisation of broiler chicken hybrids following the particularities of the producing areas may be the answer. Meanwhile, the poultry industry can mitigate the negative effects of abnormalities on meat quality by modulating the growth rate of birds through farming strategies and by incorporating downgraded meat into processed products.

References

ALNAHHAS, N., BERRI, C., BOULAY, M., BAÉZA, E., JÉGO, 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.

AVIAGEN (2007) Ross 308 broiler performance objectives. In-house publication, global. Aviagen Ltd., Newbridge, UK.

AVIAGEN (2012) Ross 308 broiler performance objectives. In-house publication, global. Aviagen Ltd., Newbridge, UK.

BARBUT, S. (2002) Measuring sensory and functional properties, in: Poultry Products Processing. An Industry Guide, pp. 467-511 (Florida, CRC Press).

BARBUT, S., SOSNICKI, A.A., LONERGAN, S.M., KNAPP, T., CIOBANU, D.C., GATCLIFFE, L.J., HUFF-LONERGAN, E. and WILSON, E.W. (2008) Progress in reducing the pale, soft and exudative (PSE) problem in pork and poultry meat. *Meat Science* **79**: 46-63.

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., DEBUT, M., SANTÉ-LHOUTELLIER, V., ARNOULD, C., BOUTTEN, B., SELLIER, N., BAÉZA, E., JEHL, N., JEGO, Y., DUCLOS, M.J. and LE BIHAN-DUVAL, E. (2005) Variations in chicken breast meat quality: Implications of struggle and muscle glycogen content at death. *British Poultry Science* **46**: 572-579.

BRANCIARI, R., MUGNAI, C., MAMMOLI, R., MIRAGLIA, D., RANUCCI, D., DAL BOSCO, A. and CASTELLINI, C. (2009) Effect of genotype and rearing system on chicken behavior and muscle fiber characteristics. *Journal of Animal Science* **87**: 4109-4117.

BREWER, V.B., KUTTAPPAN, V.A., EMMERT, J.L., MEULLENET, J.F. and OWENS, C. M. (2012) Big-bird programs: Effect of strain, sex, and debone time on meat quality of broilers. *Poultry Science* **91**: 248-254.

CAVANI, C., PETRACCI, M., TROCINO, A. and XICCATO, G. (2009) Advances in research on poultry and rabbit meat quality. *Italian Journal of Animal Science* **8**: 741-750.

DUCLOS, M.J., BERRI, C. and LE BIHAN-DUVAL, E. (2007) Muscle growth and meat quality. *Journal Applied Poultry Research* **16**: 107-112

FERREIRA, T.Z., CASAGRANDE, R.A., VIEIRA, S.L., DRIEMEIER, D. and KINDLEIN, L. (2014) An investigation of a reported case of white striping in broilers. *Journal Applied Poultry Research* **23**: 748-753.

FLETCHER, D.L. (2002) Poultry meat quality. *World's Poultry Science Journal* **58**: 131-145.

FLETCHER, D.L. (2004) Further processing of poultry, in: MEAD, G.C. (Ed) *Poultry Meat Processing and Quality*, pp. 108-134 (Florida, CRC Press).

GUARDIA, S., LESSIRE, M., CORNIAUX, A., METAYER-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 colour of broiler breast meat. *Poultry Science* **93**: 1764-1773.

GUETCHOM, B., VENNE, D., CHÉNIER, S. and CHORFI, Y. (2012) Effect of extra dietary vitamin E on preventing nutritional myopathy in broiler chickens. *Journal Applied Poultry Research* **21**: 548-555.

HAVENSTEIN, G.B., FERKET, P.R. and QURESHI, M.A. (2003a) Carcass composition and yield of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diet. *Poultry Science* **82**: 1509-1518.

HAVENSTEIN, G.B., FERKET, P.R. and QURESHI, M.A. (2003b) Growth, liveability, and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. *Poultry Science* **82**: 1500-1508.

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.

KIJOWSKI, J., KUPIŃSKA, E., STANGIERSKI, J., TOMASZEWSKA-GRAS, J. and SZABLEWSKI, T. (2014) Paradigm of deep pectoral myopathy in broiler chickens. *World's Poultry Science Journal* **70**: 125-138.

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

KUTTAPPAN, V.A., BREWER, V.B., CLARK, F.D., MCKEE, S.R., MEULLENET, J.F., EMMERT, J.L. and OWENS, C.M. (2009) Effect of white striping on the histological and meat quality characteristics of broiler fillets. *Poultry Science* **88 (E-Suppl. 1)**: 136-137.

KUTTAPPAN, V.A., BREWER, V.B., MAUROMOUSTAKOS, A., MCKEE, S.R., EMMERT, J.L., MEULLENET, J.F. and OWENS, C.M. (2013a) Estimation of factors associated with the occurrence of white striping in broiler breast fillets. *Poultry Science* **92**: 811-819.

KUTTAPPAN, V.A., GOODGAME, S.D., BRADLEY, C.D., MAUROMOUSTAKOS, A., HARGIS, B.M., WALDROUP, P.W. and OWENS, C.M. (2012b) Effect of different levels of dietary vitamin E (DL-α-tocopherol acetate) on the occurrence of various degrees of white striping on broiler breast fillets. *Poultry Science* **91**: 3230-3235.

KUTTAPPAN, V.A., HUFF, G.R., HUFF, W.E., HARGIS, B.M., APPLE, J.K., COON, C. and OWENS, C.M. (2013c) Comparison of hematologic and serologic profiles of broiler birds with normal and severe degrees of white striping in breast fillets. *Poultry Science* **92**: 339-345.

KUTTAPPAN, V.A., LEE, Y.S., ERF, G.F., MEULLENET, J.F., MCKEE, S.R. and OWENS, C.M. (2012c) Consumer acceptance of visual appearance of broiler breast meat with varying degrees of white striping. *Poultry Science* **91**: 1240-1247.

KUTTAPPAN, V.A., SHIVA PRASAD, H.L., SHAW, D.P., VALENTINE, B.A., HARGIS, BM HARGIS, F.D., MCKEE, S.R. and OWENS, C.M. (2013b) Pathological changes associated with white striping in broiler breast muscles. *Poultry Science* **92**: 331-338.

LE BIHAN-DUVAL, E., DEBUT, M., BERRI, C., SELLIER, N., SANTÉ-L'HOUTELLIER, V., JÉGO, Y. and BEAUMONT, C. (2008) Chicken meat quality: genetic variability and relationship with growth and muscle characteristics. *BMC Genetics* **9**: 53.

LORENZI, M., MUDALAL, S., CAVANI, C. and PETRACCI, M. (2014) Incidence of white striping under commercial conditions in medium and heavy broiler chickens in Italy. *Journal Applied Poultry Research* **23**: 754-758.

MACRAE, V.E, MAHON, M., GILPIN, S., SANDERCOCK, D.A. and MITCHELL, M.A. (2006) Skeletal muscle fibre growth and growth associated myopathy in the domestic chicken (*Gallus domesticus*). *British Poultry Science* **47**: 264-272.

MAHON, M. (1999) In: Poultry Meat Science. RICHARDSON, R.I. & MEAD, G.C. (Eds), pp. 19-64 (CABI Publishing Oxon England).

MALLIA, J.G., BARBUT, S., VAILLANCOURT, J.P., MARTIN, S.W. and MCEWEN, S.A. (2000a) Roaster breast meat condemned for cyanosis: A dark firm dry-like condition? *Poultry Science* **79**: 908-912.

MALLIA, J.G., HUNTER, B., VAILLANCOURT, J.P., IRWIN, R., MUCKLE, C.A., MARTIN, S.W. and MCEWEN, S.A. (2000b) Bacteriological and histological profile of turkeys condemned for cyanosis. *Poultry Science* **79**: 1194-1199.

MITCHELL, M.A. (1999) In: Poultry Meat Science. RICHARDSON, R.I. & MEAD, G.C. (Eds), pp 65-98 (CABI Publishing Oxon England).

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*, *doi:10.1017/S175173111400295X.*

PETRACCI, M. and CAVANI, C. (2012) Muscle growth and poultry meat quality issues. *Nutrients* **4**: 1-12.

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

PETRACCI, M., BIANCHI, M. and CAVANI, C. (2010) Preslaughter handling and slaughtering factors influencing poultry product quality. *World's Poultry Science Journal* **66**: 17-26.

PETRACCI, M., BIANCHI, M., MUDALAL, S. and CAVANI, C. (2013a) Functional ingredients for poultry meat products. *Trends in Food Science & Technology* **33**: 27-39.

PETRACCI, M., MUDALAL, S., BABINI, E. and CAVANI, C. (2014) Effect of white striping on chemical composition and nutritional value of chicken breast meat. *Italian Journal of Animal Science* **13**: 179-183.

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

PICARD, B., LEFAUCHEUR, L., BERRI, C. and DUCLOS, M.J. (2002) Muscle fibre ontogenesis in farm animal species. *Reproduction Nutrition Development* **42**: 415-431.

PUOLANNE, E. and RUUSUNEN, M. (2014) The utilization of poultry breast muscle of different quality. Retrieved on 29 July 2014 from http://prezi.com/yt3v1aavvkbm/?utm_campaign=share&utm_medium=copy&rc=ex0share.

QIAO, M., FLETCHER, D.L., NORTHCUTT, J.K. and SMITH, D.P. (2002) The relationship between raw broiler breast meat color and composition. *Poultry Science* **81**: 422-427.

SANDERCOCK, D.A. and MITCHELL, M.A. (2003) Myopathy in broiler chickens: A role for Ca2 +-activated phospholipase A (2). *Poultry Science* **82**: 1307-1312.

SANDERCOCK, D.A., BARKER, Z.E., MITCHELL, M.A. and HOCKING, P.M. (2009) Changes in muscle cell cation regulation and meat quality traits are associated with genetic selection for high body weight and meat yield in broiler chickens. *Genetics, Selection and Evolution* **41**: 1-8.

SANDERCOCK, D.A., HUNTER, R.R., MITCHELL, M.A. and HOCKING, P.M. (2006) Thermoregulatory capacity and muscle membrane integrity are compromised in broilers compared with layers at the same age or body weight. *British Poultry Science* **47**: 322-329.

SANDERCOCK, D.A., HUNTER, R.R., NUTE, G.R., MITCHELL, M.A. and HOCKING, P.M. (2001) Acute heat stress-induced alterations in blood acid-base status and skeletal muscle membrane integrity in broiler chickens at two ages: Implications for meat quality. *Poultry Science* **80**:418-425.

SCHEUERMANN, G.N., BILGILI, S.F., TUZUN, S. and MULVANEY, D.R. (2004) Comparison of chicken genotypes: Myofiber number in pectoralis muscle and myostatin ontogeny. *Poultry Science* **83**: 1404-1412.

SCHREURS, F.J.G. (2000) Post-mortem changes in chicken muscle. *World's Poultry Science Journal* 56: 319-346.

SILLER, W.G. (1985) Deep pectoral myopathy: A penalty of successful selection for muscle growth. *Poultry Science* **64**: 1591-1595.

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.

SOLOMON, M.B., VAN LAACK, R.L.J.M. and EASTRIDGE, J.S (1998) Biophysical basis of Pale, Soft, Exudative (PSE) pork and poultry muscle: a review. *Journal of Muscle Foods* **9**: 1-11.

VAN LAACK, R.L.J.M., LIU, C.-H., SMITH, M.O. and LOVEDAY, H.D. (2000) Characteristics of pale, soft, exudative broiler breast meat. *Poultry Science* **79**: 1057-1061.

WANG, Y., LEHANE, C., GHEBREMESKI, K. and CRAWFORD, M.A. (2010) Modern organic and broiler chickens sold for human consumption provide more energy from fat than protein. *Public Health Nutrition* **13**: 400-408.

ZIMERMANN, F.C., FALLAVENA, L.C.B., SALLE, C.T.P., MORAES, H.L.S., SONCINI, R.A., BARRETA, M.H. and NASCIMENTO, V.P. (2012) Downgrading of heavy broiler chicken carcasses due to myodegeneration of the *Anterior latissimus d*orsi: pathologic and epidemiologic studies. *Avian Diseases* **56**: 418-421.