ISSN 1682-8356
ansinet.org/ijps

INTERNATIONAL JOURNAL OF

# POULTRY SCIENCE

ANSInet
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan
Mob: +92 300 3008585, Fax: +92 41 8815544
E-mail: editorijps@gmail.com

International Journal of Poultry Science 3 (4): 253-258, 2004


# Induced Red Discoloration of Broiler Breast Meat: ii. Effect of Cook Temperature and Freezing

D.P. Smith and J.K. Northcutt
USDA, Agricultural Research Service, Russell Research Center,
950 College Station Road, Athens, GA 30605, USA
E-mail: dpsmith@saa.ars.usda.gov

**Abstract:** Consumers and customers typically reject fully-cooked chicken that has a red/bloody appearance even if the product is otherwise safe and wholesome. Unfortunately, chicken parts and whole bird products may exhibit this problem on a consistent basis. This study was conducted to intentionally induce a red/bloody appearance in fully-cooked chicken to create a model for studying methods to control this defect. Five trials were conducted using bony marrow (harvested from the interior of epiphyseal end caps) from either fresh femurs (three trials) or frozen femurs (two trials) that were prepared and placed in contact with chopped broiler breast meat. Meat and marrow were packed into glass tubes and heated to one of three endpoint temperatures (74, 79, or 85°C). Five replicate tubes were prepared for each endpoint temperature in each trial (n = 75). After cooking and immediate cooling, CIE lightness (L*) and redness (a*) was determined for both the surface of the meat adjacent to the bony marrow and the surface of the marrow. The surfaces of the meat from samples prepared with fresh marrow were darker (lower L* values) and redder (higher a* values) than control meat surface samples. Each higher endpoint cook temperature resulted in a significantly ($P < 0.05$) lighter and less red sample. The meat exposed to frozen marrow was affected by temperature to a lesser extent as lightness increased only at 79°C and redness values did not significantly decrease from 79 to 85°C. Lightness of the marrow surface was unaffected by freezing or endpoint cook temperature. Marrow surface redness was decreased as cook temperature increased and freezing appeared to decrease the redness of samples cooked at either 74 or 79°C. Bony marrow was effective at inducing a red, bloody discoloration in breast meat samples. Higher cook temperatures and freezing femurs (before harvesting marrow) improved meat lightness and redness values, although not to control values.

**Key words:** Red discoloration, meat redness, bone marrow, cook temperature

## Introduction

Color of poultry meat is an important factor related to consumer acceptance or rejection. A number of factors affect poultry meat appearance and color and several of these may have a negative effect on meat color. Perhaps the most commonly reported complaint for cooked chicken meat color is pink meat, while other complaints include bone darkening and red (or bloody) appearance of bone-in chicken. Of these problems, the meat pinking and red/bloody poultry parts are critical for consumer rejection as they directly relate to an undercooked appearance of the product.

Poultry meat pinking has been and continues to be a problem reported by producers and consumers. An abundance of research has shown many factors may be involved in producing or intensifying poultry meat pinking. As birds age, they tend to have redder muscles (Froning and Hartung, 1967; Mugler *et al*., 1970). The strain of the bird may also affect raw muscle redness (Froning *et al*., 1968). Conditions affecting live birds that contribute to pinking (as shown by increased muscle redness) include dietary nitrates and nitrites, moldy feed materials, dietary yeast supplements and milo used as a carbohydrate source (Froning *et al*., 1969b; Wu *et al*., 1994; Akiba *et al*., 2001; Smith *et al*., 2002). Stress as caused by either excitation or increased temperature prior to slaughter reportedly produces redder muscle (Ngoka *et al*., 1982; Froning *et al*., 1978). Catching and transport can also increase muscle redness from lack of feed withdrawal to exposure of automobile exhaust (Smith *et al*., 2002; Froning *et al*., 1969a). Researchers have reported that muscle hemorrhages result from mishandling or improper stunning. These injuries could contribute to localized meat redness from blood accumulation (Walker *et al*., 1993; Bilgili, 1992). At the plant, stunning electrically produced redder meat than gas stunning methods (Savenije *et al*., 2002). Electrical stimulation also produced redder muscle (Lyon *et al*., 1998). Meat deboned early postmortem was redder than meat aged longer on the carcass (Young and Lyon, 1997; Young *et al*., 1996). Marination has been reported to affect meat redness in various ways and its effect was partially reviewed by Smith and Northcutt (2004). Exposure of meat to nitrites or nitrates in ice or water significantly increases muscle redness (Mugler *et al*., 1970; Nash *et al*., 1985). Raw meat was redder earlier when stored under refrigeration, then redness decreased as days of storage increased (Yang and

Chen, 1993). Freezing raw meat increases redness (Lyon *et al.*, 1976). Redness is typically more prevalent when meat is cooked at lower endpoint temperatures and redness decreases as cooking temperatures increase (Heath and Owens, 1992; Helmke and Froning, 1971). Certain types of ovens, oven burners and cooking methods can increase pinking (Pool, 1956; Cornforth *et al.*, 1998). Several researchers have attempted to resolve the pink meat problem by adding various substances and others have intentionally induced meat pinking in the laboratory to facilitate this type of research (Schwarz *et al.*, 1999; Slesinski *et al.*, 2000; Holownia *et al.*, 2003).

Intense redness, sometimes accompanied by "bloody" juices, has been observed in the commercial further processing industry and reported by Smith and Northcutt (2003). This red/bloody meat may be related to a phenomenon called bone darkening as both occur when bones are present in cooked meat. Bone darkening, studied in the earlier stages of the poultry processing industry when freezing and cooking were first conducted commercially, is defined as a condition where the surface of the bone and adjacent muscle tissue are discolored to a dark reddish brown or black after cooking. The discoloration is apparently due to bone marrow passing through the bone and onto adjacent tissues (usually after freezing), which then darkens when heated (Koonz and Ramsbottom, 1947). They also found less discoloration in older birds, leading to the conclusions that bones in younger animals are less calcified and therefore are more porous and that younger birds have more red marrow (vs. yellow marrow) than older birds. Brant and Stewart (1950) reported the following based on their research: freezing hemolyzed red blood cells and allowed release of hemoglobin; freezing also caused an increase in bone porosity that allowed hemoglobin leakage; and, bone marrow was the only source of the pigment that caused darkening. Ellis and Woodroof (1959) reported that the diet of live birds may affect darkening, as either lower calcium or higher vitamin D levels worsened darkening. They also reported parts from male broilers were more susceptible to bone darkening than females. Researchers attempting to reduce or eliminate bone darkening found that pre-cooking prior to freezing reduced darkening, with microwave heating more effective at reducing darkening than other types of cooking methods (Essary, 1958; Ellis and Woodroof, 1959). Different freezing regimens have also been tried, with little effect (Spencer *et al.*, 1961; Streeter and Spencer, 1973). However, others found that rapid and lower temperature freezing did lessen bone darkening (Li *et al.*, 1969; Cunningham, 1974). Lyon and Lyon (1986) found that a longer bleed out time could reduce bone darkening and that different cook methods could affect the degree of discoloration.

The red/bloody discoloration appears to also result from leakage of marrow constituents onto surrounding tissue, but without the subsequent darkening after cooking. Smith and Northcutt (2004) reported that using blood and fatty bone marrow in an attempt to induce red/bloody discoloration significantly darkened and reddened chicken meat, similar to reports of bone darkening, but that a piece of bony marrow was found to have caused an intense, bloody red discoloration in one sample. Therefore this study was conducted to determine if bony marrow would cause a red/bloody discoloration for use as an effective method for consistently producing this defect in the laboratory. Higher endpoint cooking temperature and pre-freezing marrow was also studied to determine effects on induced red/bloody discoloration.

## Materials and Methods

Fresh, refrigerated boneless, skinless broiler breast meat was obtained from a local retail store for all five trials. Breast meat was refrigerated at 4°C no longer than 24 h, then removed from refrigeration and fillets trimmed of obvious fat and connective tissue. Fillets were manually chopped into small pieces and blended for 30 s in a food processor for use on the same day of preparation. Fresh whole thighs were also obtained from a local retail store. For each of three trials, the whole thighs were held at 4°C until removed from refrigeration, manually deboned and femurs cleaned of external tissue. For each of two trials, the thighs were frozen a minimum of 12 h, then thawed 2 h at ambient room temperature prior to deboning and femur removal and cleaning, as described previously. The epiphyseal end caps were removed from femurs and the diaphysis portion, containing the fatty marrow, was discarded. The exterior bone was cut away from the epiphyseal caps, leaving irregularly shaped blocks of porous, bony marrow. These small blocks of bony marrow (and any small amount of adhering bone) were blended for 20 s in a food processor to a thick, granular paste, then used the same day of preparation.

A total of eighteen glass tubes for each of the five trials (three groups with refrigerated marrow, two with frozen marrow) were prepared as follows: breast meat was weighed into 10 g portions and the bony marrow paste was weighed into 1 g portions. Approximately 5 g of meat was placed into one end of a glass tube (OD = 20 mm, ID = 17 mm X 200 mm length), then 1 g of marrow was added, then the remainder of the original 10 g of breast meat was added. The tube was then sealed on the bottom only with a # 2 rubber stopper. Fifteen tubes were prepared in this way with meat and marrow. Three additional tubes were filled with only breast meat as a non-marrow control. Prepared tubes were placed in a pre-heated 95°C circulating water bath until cooked to an internal temperature (as recorded by an inserted thermocouple) of 74°C (~ 2 min), 79°C (~ 3 min), or 85°C

(~ 4.5 min). Five tubes with meat and marrow and one with meat only (control) were removed as each increasing endpoint temperature was reached. Removed tubes were immediately placed in an ice water bath for 1 h. Stoppers were removed and the cooked mixture "plugs", 16 mm in diameter, were taken from the tubes and manually broken into halves (where the bony marrow divided the meat mixture). Control tube plugs were sliced in half with a razor blade. A colorimeter (Minolta Chroma Meter 300, Minolta Corp., Ramsey, NJ 07446) was used to record CIE L* (lightness) and a* (redness) values (triplicate readings averaged together) from the flat side of the bony marrow surface, from one of the ends of the meat plug (that was adjacent to the marrow) and from the flat side of the sliced control plug. Prior to measuring meat color, the colorimeter was standardized with a white tile (reference number 13533123; Y = 92.7, x = 0.3133, y = 0.3193).

Data were pooled across replication of tubes and across trials, by their marrow pre-freezing treatment (refrigerated or frozen). The main effect of endpoint cook temperature was tested with general linear models (GLM) procedures of the SAS software (SAS Institute, 1999). Means, where significant, were separated by Duncan's multiple range test ($P < 0.05$).

## Results

Lightness (L*) and redness (a*) means and SEM for the meat surface of samples cooked at 74, 79 and 85°C and discolored by either fresh or frozen marrow are shown in Table 1. For samples using fresh marrow, cooking to a higher endpoint temperature significantly increased lightness values at each temperature measured from 45.59 to 51.65 to 56.80 at 74, 79 and 85°C, respectively. Redness values from fresh marrow were significantly reduced by incremental temperature, from 22.19 to 14.19 to 7.41 at 74, 79 and 85°C, respectively. Lightness values of samples composed of frozen marrow were also affected by temperature, with values increasing when temperature was changed from 74 to 79°C (49.81 to 56.38), but the value at 85°C (55.01) was not significantly different than either the 74 or 79°C values. Redness of frozen marrow samples decreased when temperature was increased from 74 to 79°C (12.95 vs. 10.14, respectively), but the value at 85°C (7.84) was not different from that found after cooking to 79°C. Overall, frozen marrow lightness values appeared to be lighter and less red than fresh marrow samples at the lowest recorded temperature of 74°C, but at 85°C lightness and redness values were similar for fresh and frozen marrow.

The surface of the marrow was also evaluated for lightness and redness values after cooking (Table 2.) Lightness values of the samples from fresh marrow were not affected by endpoint cook temperature, ranging from 35.04 at 74°C to 35.83 at 85°C. Redness values of the fresh marrow samples significantly decreased with each step of increasing temperature, from 20.51 at 74°C to 14.90 at 79°C, then to 7.63 at 85°C. For frozen marrow samples, lightness values were not significantly affected by endpoint cook temperature. Values were 35.10, 35.80 and 35.34 at 74, 79 and 85°C, respectively. Redness values were decreased by each level of increasing temperature, from 13.39 to 10.54 to 7.13 at 74, 79 and 85°C, respectively. Lightness values of marrow samples seemed to not be affected either by freezing before use or by endpoint cook temperature. The redness values seemed to be lower for frozen marrow at 74°C than for fresh marrow (20.51 vs. 13.39, respectively) but values of samples cooked to the higher temperature of 85°C were much closer together (7.63 fresh vs. 7.13 frozen).

Lightness values (n = 5) for the control samples (cooked without marrow) did not differ due to cooking temperature and averaged 79.24 at 74°C, 79.24 at 79°C

Table 1: L* (lightness) and a* (redness) means and SEM for the surface of chopped broiler breast meat exposed to bony marrow taken from the femurs of either fresh or frozen broiler thighs and cooked to endpoint temperatures of either 74, 79 or 85°C (165, 175 and 185 F° respectively)

| Marrow Form | Endpoint cook | Meat (cooked surface) | |
|---|---|---|---|
| | C° | L* | a* |
| Fresh[1] | 74 | 45.59[c]± 0.77 | 22.19[a] ±1.34 |
| | 79 | 51.65[b]± 1.60 | 14.19[b] ±1.66 |
| | 85 | 56.80[a]± 1.63 | 7.41[c]±0.53 |
| Frozen[2] | 74 | 49.81[b]± 1.32 | 12.95[a] ±0.73 |
| | 79 | 56.38[a]± 2.59 | 10.14[b] ±1.36 |
| | 85 | 55.01[ab] ±1.66 | 7.84[b]±0.55 |

[a-c] Means in columns within marrow form with differing superscripts are significantly different. [1]n=15, [2]n=10

Table 2: L* (lightness) and a* (redness) means and SEM for the surface of bony marrow taken from femurs of either fresh or frozen broiler thighs and cooked to endpoint temperatures of either 74, 79, or 85°C (165, 175 and 185°F, respectively)

| Marrow Form | Endpoint cook | Marrow (cooked surface) | |
|---|---|---|---|
| | C° | L* | a* |
| Fresh[1] | 74 | 35.04±0.35 | 20.51[a]±2.10 |
| | 79 | 35.17±0.72 | 14.90[b]±2.28 |
| | 85 | 35.83±0.50 | 7.63[c]±0.32 |
| Frozen[2] | 74 | 35.10±0.51 | 13.39[a]±0.97 |
| | 79 | 35.80±0.90 | 10.54[b]±0.54 |
| | 85 | 35.34±0.44 | 7.13[c]±0.23 |

[a-c] Means in columns within marrow form with differing superscripts are significantly different. [1]n=15, [2]n=10

and 79.35 at 85°C. There also was no difference in average redness values of control samples (0.54, 0.40 and -0.11 at 74, 79 and 85°C, respectively).

## Discussion

Cooking to higher endpoint temperatures lightened and decreased redness of broiler breast meat samples cooked in contact with bony marrow. Even at the highest temperature tested (85°C), the meat surface was darker and redder than control samples (meat cooked without marrow). Freezing marrow beforehand seemed to lessen the darkening and reddening effects on the meat's surface. The samples cooked at lower temperatures of 74 and 79°C and composed of fresh marrow exhibited the red/bloody discoloration, while samples cooked at 85°C or using frozen marrow at any temperature resembled descriptions given for bone darkening (dark reddish-brown or black). The lightness and redness values in this study (56.80 and 7.41, respectively) for breast meat adjacent to fresh marrow and cooked to 85°C were comparable to the lightness and redness values reported by Smith and Northcutt (2004) for fatty bone marrow mixed with breast meat and cooked to 74°C (58.62 and 7.10, respectively). Overall, bony marrow from fresh broiler femurs significantly increased redness and darkness of broiler breast meat as compared to control values and these effects were somewhat lessened with increasing cook temperatures. Increasing the endpoint cook temperature usually increases lightness and decreases redness of turkey dark meat rolls (Helmke and Froning, 1971) and broiler thigh meat (Davis and Franks, 1995). Increasing the endpoint cook temperature also has been shown to decrease redness, but did not increase lightness of broiler breast muscle (Heath and Owens, 1992). Additional heat during reheating can reduce redness values of cooked and frozen poultry products, but only at high temperatures (82°C) and with a decrease in yield (Lyon and Lyon, 1975).

The surface lightness of the marrow cooked at different endpoint temperatures was unaffected both by temperature and pre-freezing. Surface redness of marrow responded in the same manner as the meat surface, where increasing endpoint temperature decreased redness, whether the marrow used was fresh or frozen. Frozen marrow was less red than fresh marrow at the lower temperatures, but cooking to higher temperatures brought the 85°C redness values very close together, without regard for whether the marrow was fresh or frozen. The same pattern was evident for the meat surface redness and lightness values. This indicates that higher heat is likely denaturing the proteins responsible for the red pigmentation (probably globins), which have already been partially damaged by freezing and are therefore less red even at the lower cook temperatures. The data also indicate there is some ultimate point of maximum lightness and minimum redness of discolored samples achievable by pre-freezing and/or cooking to a higher endpoint temperature, although values would not be comparable to control (non-discolored) samples. The change in meat color as endpoint temperatures increased was likely due only to the typical change in color associated with cooking meat since the lightness of the marrow itself was unaffected by temperature. The marrow did seem to directly influence redness of meat, as values were similar at each endpoint temperature between meat and marrow surfaces; and, as temperature increased, redness decreased by the same amount in meat and marrow values. Therefore, bony marrow was the primary cause of meat redness.

Bone darkening has been shown to be related to freezing of bone-in parts prior to cooking, but there is variation in reports regarding the effects of freezing, cooking and even raw bone observations on the development of darkening. The type and rate of freezing has been reported to have no effect on darkening (Brant and Stewart, 1950; Spencer *et al.*, 1961; Streeter and Spencer, 1973), although rapid low temperature freezing may improve darkening (Li *et al.*, 1969; Cunningham, 1974). Cook method (and endpoint temperature) has been reported to have no effect on darkening (Brant and Stewart, 1950), although others have found cook method does affect darkening (Cunningham and Lee, 1975; Lyon and Lyon, 1986). There is even disagreement in results within a cook method on the effects of bone darkening, as some report microwave heating decreases darkening (Essay, 1958; Ellis and Woodroof, 1959) and others report microwave heating increases the intensity of darkening (Cunningham and Lee, 1975). There has been some variation reported in the rate of darkening of frozen and thawed uncooked bones, as some immediately darkened while others took several days to darken (Koonz and Ramsbottom, 1947). The variations reported in bone darkening research may be related to the sporadic nature of red/bloody discoloration. Also, a possible link to a common cause (bone marrow) of both bone darkening and red/bloody discoloration may be found in a report by Lyon *et al.* (1976), who found that removal of the femur prior to cooking significantly decreased meat redness in broiler thighs.

Researchers have reported that discolored areas of commercially produced breast meat products range from 4.15 to 8.07 for redness (CIE a*) values (Smith and Northcutt, 2003). In the current study meat redness values for meat adjacent to fresh marrow (7.41) and frozen marrow (7.84) and cooked to 85°C fall within this range. A likely source of red pigmentation from bony marrow is hemoglobin (Brant and Stewart, 1950). Another factor causing redness could be nitric oxide, which has been associated with meat pinking (Pool,

1956) and now reported to exist in certain bone marrow cells. Nitric oxide is associated with bone resorption and growth; the levels are higher in young animals and levels increase in response to bone stress or as a result of an immune response (Ralston, 1997; van't Hof and Ralston, 2001). These factors generally apply to broiler chickens as they are young, fast growing animals (with stressed leg and thigh bones) and typically exhibit immune responses resulting from vaccinations or exposure to microbes in the growout house. Further research is needed to determine and further characterize the factors responsible for causing redness.

This study shows that cooking to higher endpoint temps can reduce red/bloody discoloration; a lower endpoint temperature that reduces discoloration is possible if the product is frozen before cooking. Processors are unlikely to find either option attractive due to increased expense, loss of yield and possible impaired functionality of the product. Results show that this system (broiler breast meat adjacent to fresh bony marrow from femurs cooked to temperatures of 79 to 84°C) is effective at consistently reproducing a red/bloody discoloration defect in the laboratory. The model will be used to screen additives or methods thought to prevent or effectively reduce red discoloration in fully-cooked bone-in chicken meat.

## References


Akiba, Y., K. Sato, K. Takahashi, K. Matsushita, H. Komiyama, H, Tsunekawa and H. Nagao, 2001. Meat color modification in broiler chickens by feeding yeast *Phaffia rhodozyma* containing high concentrations of astaxanthin. J. Appl. Poult. Res., 10: 154-161.

Brant, A.W. and G.F. Stewart, 1950. Bone darkening in frozen poultry. Food Tec., 4:168-174.

Bilgili, S. F., 1992. Electrical stunning of broilers - basic concepts and carcass quality implications: A Rev., J. Appl. Poult. Res., 1: 135-146.

Cornforth, D.P., J.K. Rabovitser, S. Ahuja, J.C. Wagner, R. Hanson, B. Cummings and Y. Chudnovsky, 1998. Carbon monoxide, nitric oxide and nitrogen dioxide levels in gas ovens related to surface pinking of cooked beef and turkey. J. Agri. Food Chem., 46: 255-261.

Cunningham, F.E., 1974. Effect of freezing temperature on bone darkening in cooked broilers. Poult. Sci., 53: 425-427.

Cunningham, F.E. and H.W. Lee, 1975. Influence of thawing and cooking procedures on selected characteristics of broilers. Poult. Sci., 54: 903-908.

Davis, C.E. and D.L. Franks, 1995. Effect of end-point temperature and storage time on color and denaturation of myoglobin in broiler thigh meat. Poult. Sci., 74: 1699-1702.

Ellis, C. and J.G. Woodroof, 1959. Prevention of darkening in frozen broilers. Food Tech., 13: 533-588.

Essary, E.O., 1958. Influence of microwave heat on bone discoloration of frozen fryers. Poult. Sci., 37: 1202.

Froning, G.W., A.S. Babji and F.B. Mather, 1978. The effect of preslaughter temperature, stress, struggle and anesthetization on color and textural chrarcteristics of turkey muscle. Poult. Sci., 57: 630-633.

Froning, G.W., F.B. Mather, J. Daddario and T.E. Hartung, 1969a. Effect of automobile exhaust fume inhalation by poultry immediately prior to slaughter on color of meat. Poult. Sci., 48: 485-487.

Froning, G.W., J. Daddario and T.E. Hartung, 1968. Color and myoglobin concentration in turkey meat as affected by age, sex and strain. Poult. Sci., 47: 1827-1835.

Froning, G.W., J. Daddario, T.E. Hartung, T.W. Sullivan and R.M. Hill, 1969b. Color of poultry meat as influenced by dietary nitrates and nitrites. Poult. Sci., 48: 668-673.

Froning, G.W. and T.E. Hartung, 1967. Effect of age, sex and strain on color and texture of turkey meat. Poult. Sci., 46: 1261.

Heath, J.L. and S.L. Owens, 1992. Effect of heating variables and storage on color of chicken cooked and stored in polyester pouches. Poult. Sci., 71: 1773-1780.

Helmke, A. and G.W. Froning, 1971. The effect of end-point cooking temperature and storage on the color of turkey meat. Poult. Sci., 50: 1832-1836.

Holownia, K., M.S. Chinnan, A.E. Reynolds and P.E. Koehler, 2003. Evaluation of induced color changes in chicken breast meat during simulation of pink color defect. Poult. Sci., 82: 1049-1059.

Koonz, C.H. and J.M. Ramsbottom, 1947. Influence of freezing on color of bones and adjacent tissue. Food Res., 12: 393-399.

Li, K.C., E.K. Heaton and J.E. Marion, 1969. Freezing chicken thighs by liquid nitrogen and sharp freezing process. Food Tech., 23: 107-109.

Lyon, C.E. and B.G. Lyon, 1975. Doneness of commercially cooked broiler thighs as indicated by objective color method. J. Food Sci., 40: 1091-1092.

Lyon, B.G. and C.E. Lyon, 1986. Surface dark spotting and bone discoloration in fried chicken. Poult. Sci., 65: 1915-1918.

Lyon, C.E., B.G. Lyon and J.A. Dickens, 1998. Effects of carcass stimulation, deboning time and marination on color and texture of broiler breast meat. J. Appl. Poult. Res., 7: 53-60.

Lyon, C.E., W.E. Townsend and R.L. Wilson, Jr., 1976. Objective color values of non-frozen and frozen broiler breasts and thighs. Poult. Sci., 55: 1307-1312.

Mugler, D.J., J.D. Mitchell and A.W. Adams, 1970. Factors affecting turkey meat color. Poult. Sci., 49: 1510-1513.

Nash, D.M., F.G. Proudfoot and H.W. Hulan, 1985. Pink discoloration in cooked broiler chicken. Poult. Sci., 64: 917-919.

Ngoka, D.A., G.W. Froning, S.R. Lowry and A.S. Babji, 1982. Effects of sex, age, preslaughter factors and holding conditions on the quality characteristics and chemical composition of turkey breast muscles. Poult. Sci., 61: 1996-2003.

Pool, M.F., 1956. Why does some turkey turn pink? Turkey World, 31: 69-74.

Ralston, S.H., 1997. Nitric oxide and bone:what a gas! Br. J. Rheum., 36: 831-838.

SAS, 1999. User's Guide, Version 8, SAS Institute, Inc., Cary, NC.

Savenije, B., F.J.G. Schreurs, H.A. Winkelman-Goedhart, M.A. Gerritzen, J. Korf and E. Lambooij, 2002. Effects of feed deprivation and electrical, gas and captive needle stunning on early postmortem muscle metabolism and subsequent meat quality. Poult. Sci., 81: 561-571.

Schwarz, S.J., J.R. Claus, H. Wang, N.G. Marriott, P.P. Graham and C.F. Fernandes, 1999. Inhibition of pink color development in cooked, uncured turkey breast through ingredient incorporation. Poult Sci., 78: 255-266.

Slesinski, A.J., J.R. Claus, C.M. Anderson-Cook, W.E. Eigel, P.P. Graham, G.E. Lenz and R.B. Noble, 2000. Ability of various dairy proteins to reduce pink color development in cooked ground turkey breast meat. J. Food Sci., 65: 417-420.

Smith, D.P., C.E. Lyon and B.G. Lyon, 2002. The effect of age, dietary carbohydrate source and feed withdrawal on broiler breast fillet color. Poult. Sci., 81: 1584-1588.

Smith, D.P. and J.K. Northcutt, 2003. Red discoloration of fully cooked chicken products. J. Appl. Poult. Res., 12: 515-521.

Smith, D.P. and J.K. Northcutt, 2004. Induced red discoloration of broiler breast meat: i. Effect of blood, bone marrow and marination. Int. J. Poult. Sci., 3: 248-252.

Spencer, J.V., E.A. Sauter and W.J. Stadelman, 1961. Effect of freezing, thawing and storing broilers on spoilage, flavor and bone darkening. Poult. Sci., 40: 918-920.

Streeter, E.M. and J.V. Spencer, 1973. Cryogenic and conventional freezing of chicken. Poult. Sci. 52: 317-325.

van't Hof, R.J. and S.H. Ralston, 2001. Nitric oxide and bone. Immunology, 103: 255-261.

Yang, C.C. and T.C. Chen, 1993. Effects of refrigerated storage, pH adjustment and marinade on color of raw and microwave cooked chicken meat. Poult. Sci., 72: 355-362.

Young, L.L. and C.E. Lyon, 1997. Effect of postchill aging and sodium tripolyphosphate on moisture binding properties, color and Warner-Bratzler shear values of chicken breast meat. Poult. Sci., 76: 1587-1590.

Young, L.L., C.E. Lyon, J.K. Northcutt and J.A. Dickens, 1996. Effect of time post-mortem on development of pink discoloration in cooked turkey breast meat. Poult. Sci., 75: 140-143.

Walker, J.M., R.J. Buhr and D.L. Fletcher, 1993. Investigation of processing factors contributing to hemorrhagic leg syndrome in broilers. Poult. Sci., 72: 1592-1596.

Wu, W., D. Jerome and R. Nagaraj, 1994. Increased redness in turkey breast muscle induced by fusarial culture materials. Poult. Sci., 73: 331-335.