SEGREGATING URUGUAYAN BEEF CARCASSES BY TENDERNESS UNDER COMMERCIAL CONDITIONS USING POSTMORTEM CARCASS TRAITS, pH, TEMPERATURE AND COLOR

by

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(Under the Direction of T. Dean Pringle)

ABSTRACT

This research was conducted to segregate Uruguayan beef carcasses by tenderness under commercial conditions and detect sources of its variation (age, sex, end points, chilling/pH decline rates). Postmortem carcass traits, pH (pH_1, pH_3, pH_u), temperature (T_1, T_3, T_u) and color (L*, a*, b*) of *longissimus* muscle were used as predictors of steak tenderness. Two aging times were evaluated: 7 (WBSF7) and 14 (WBSF14) days. In Experiment 1, female carcasses (n=163) were selected at one packing plant (PP). Tenderness differences were explained by dentition ($P<0.01$). Carcasses with $pH_3 < 5.8$ and $a^* \geq 20$ showed the lowest level of tenderness. WBSF14 showed a high correlation (r) with USDA lean maturity and color values ($P<0.01$). Lean and overall maturity explained 15 and 23% whereas a* accounted for 32 and 33% of WBSF7 and WBSF14 variation, respectively. A linear regression equation (QG, a*, a^{*2}, pH_u, pHu^2) to predict WBSF7 and WBSF14 showed adjusted R^2=0.34 and 0.38 and an accuracy of 75.6 and 79.5%, respectively, using a WBSF threshold of 4.5 kg. In Experiment 2, male carcasses (n=174) were selected at the same PP. USDA yield grade showed r = -0.22 and -0.22 ($P<0.05$) with WBSF7 and WBSF14.

Lean a* had r = -0.47 and -0.40 with WBSF7 and WBSF14 ($P<0.01$) and accounted for 22 and 16% of WBSF7 and WBSF14 variation. A linear regression equation (a*, pH_u, pH_u^2) showed an adjusted R^2 = 0.23 and 0.14 and an accuracy of 76.7 and 88.3% for WBSF7 and WBSF14 prediction (WBSF threshold = 3.4 kg). In Experiment 3, male carcasses (n=449) were selected at two PP. There was a significant effect of PP on tenderness ($P<0.01$). WBSF7 and WBSF14 showed r = 0.43 and 0.44 ($P<0.01$) with T_u. A linear regression equation (dentition, rib eye area, pH_u, T_u, L*, a*, b*) to predict WBSF7 and WBSF14 showed adjusted R^2=0.25 and 0.26 and an accuracy of 66.1 and 75.6% for both tenderness (WBSF threshold = 4.5 kg). Although QG, pH_u and a* measured at ribbing in Uruguayan commercial conditions could contribute to differentiate levels of beef tenderness, other differences between PP could affect segregation effectiveness.

INDEX WORDS: Beef, Female, Male, Color, pH, Temperature, Tenderness, Prediction

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CHAPTER 1

INTRODUCTION

The loss of market share in the beef industry has led to numerous strategies to create value in beef at all levels of marketing and production, in order to meet consumer expectations. The beef industry is evolving from selling a commodity to marketing a product, and branded beef programs are emerging rapidly because of this paradigm shift. This seems to be a reaction against the old way of marketing, with little concern about consumer satisfaction. As highlighted by many authors, quality improvement must be driven by the consumer's expectations and perceptions because they are the final users of the products, and because consumer's perceptions of food quality are closely related with the concept of acceptability. It is also apparent that the worldwide meat production will continue to put emphasis on meat quality with particular emphasis on palatability and leanness. One way of assuring meat quality in fresh meat products is by implementing quality management systems and on-line process control.

The meat industry in different countries (primarily the United States, New Zealand and Australia) has carried out several trials to classify carcasses into groups with similar composition and quality attributes. There is a growing interest on the part of the global meat industry to develop a carcass classification system that would more accurately predict beef palatability, particularly tenderness, and to implement different meat quality programs (ex: Tenderness Guarantee, Meat Standard of Australia and New Zealand Beef and Lamb Quality Marks). The application of carcass quality characteristics to subdivide a heterogeneous population of carcasses, and resulting beef cuts, into marketing groups could be beneficial and profitable for the meat industry. Establishing values associated with varying degrees of meat quality will allow economic incentive to drive the search for quality products to market to the consumer. The economic incentives for the industry to improve quality aspects of the meat, particularly tenderness, must be established before significant improvements in the consistency will occur.

Uruguay as a fresh meat export country (20% of Uruguayan total exports), should be allied to this strategy being developed by the main meat producing and export countries. The traditional market for the Uruguayan beef value cuts has been Europe, which has not demanded tenderness specifications, looking primarily for lean cuts. One of the goals for the Uruguayan meat industry should be to know the degree of the acceptance of its beef product by the European consumers as well as by other potential import markets (Canada, United States, Mexico, Japan, and Korea) that also demand quality attributes. However, a significant effort needs to be initiated to convince those in the Uruguayan beef industry that tenderness is something to search for, manage and market. Without information regarding economic incentives, most entities within the beef industry will continue to ignore tenderness and beef will remain variable in its eating quality and experience by the consumer.

Therefore, this study was designed to:

1. Identify effective methods for segregating beef carcasses into different groups under commercial conditions according to levels of acceptability, namely tenderness, and directed to different markets that could enhance specific markets in the meat industry.
2. Detect sources of variation in Uruguayan meat tenderness associated to animal age, sex, fatness end points, chilling and pH decline rates, and aging periods.
3. Characterize a representative Uruguayan carcass population in pH and color, because the national meat industry is more concerned with both variables from safety and condemnation standpoints, compared to their relationship with the goal of carcass segregation.

CHAPTER 2

LITERATURE REVIEW

The textural attributes and eating quality of cooked meat are dominated by the tenderness component. Many initiatives in the beef industry intending to produce fresh meat that is of an acceptable eating quality have demonstrated the realization that less tender meat is contributing to the loss of market share to others forms of protein.

Current evidence suggests that on-farm factors contribute up to 40% of the variability in meat tenderness and meat processing 60-70% of the variation (Koohmaraie et al., 1996). Thus a good quality animal processed correctly yields excellent meat processed incorrectly, it yields poor quality meat. Above all, a poor quality animal can never be converted by normal processing into excellent meat

For this study, we will consider many of the factors during meat processing that affect tenderness

Effect of subcutaneous fat on tenderness

Several studies have been conducted to evaluate the value of fat covering in preventing cold shortening or toughening. (The definitions of cold and heat shortening will be presented in "Effect of the rate of pH decline and the rate of cooling" section).

Laurent et al. (1991), removing the subcutaneous fat from the right side of steer carcasses at 1hr post mortem and the short loins at 24 h post-mortem found that the fat removed sides showed lower temperatures, higher pH values and higher Instron shear values at 3 and 10 days aging times compared with the fat intact sides (8.26 kg vs. 6.17 kg and 5.88 kg vs. 5.08 kg, respectively, $p<0.01$). These findings are concordant with results from Meyer et al. (1977), where hourly temperatures were lower for defatted sides compared to control sides and Warner Bratzler shear force (WBSF) values were lower for control sides than defatted sides (5.91 kg vs. 6.68 kg, respectively, $P<0.05$).

Koohmaraie et al. (1988) studied the role of subcutaneous fat as an insulator of beef carcasses, comparing chilling and high-temperature conditioning on bovine meat tenderness. Although fat removal reduced *longissimus* muscle temperature and increased pH of sides chilled at 0^{o}C, it had no consistent effects on WBSF values (WBSF value difference was 0.5 kg). It is important to mention that fat removed sides presented conditions (10.8^{o}C and pH 6 at 6 h) on the borderline for cold-shortening (<10^{o}C and pH>6).

May et al. (1992), in a serial slaughter trial at 28-day intervals, did not find significant differences for WBSF values between untrimmed and trimmed sides and only a small difference in sarcomere length (1.87 vs. 1.83 μm, respectively). These results suggest that subcutaneous fat had little influence on tenderness when cold-shortening conditions did not exist. Lochner et al. (1980) studied two feeding groups (fat: corn-corn silage and lean: alfalfa hay) and chilling rates (rapid:-2^{o}C, air moving and slow: 9^{o}C, air without movement). These authors concluded that tenderness was highly dependent on the muscle temperature at 2 to 4 h post-mortem and that cold shortening was not a significant cause of toughness, except in rapidly chilled lean carcasses because they reached 10^{o}C by 6 h postmortem conditions conducive to cold shortening.

Most of these studies considered the insulation effect of fat on beef carcasses and its relation to cold shortening conditions. It is also important to consider the heat shortening effect on tenderness.

Lee and Ashmore (1985) comparing Hereford carcasses coming off feedlot and grass-fed systems and chilled at 0^{o}C (LT) and 35^{o}C for 3 hr followed by 0^{o}C (HT) showed that feedlot + HT sides had greater toughness compared with feedlot + LT sides at 3 and 7 days aging. They also exhibited short sarcomere length with more variation (Table 2.1).

Table 2.1 Effect of early post-mortem temperature on tenderness and sarcomere length

	Warner Shear Force values (kgF)				Sarcomere length (μm)	
Groups	LT sides		HT sides		LT	HT
	3 d. aging	7 d. aging	3 d. aging	7 d. aging		
Feedlot	7.40 ± .17[c]	6.88 ± .09[d]	7.98 ± .13[e]	7.83 ± .10[e]	1.87±.02[b]	1.66±.04[c]
Grass-fed	10.65 ± .3[c]	8.35 ± .23[de]	9.13 ± .31[d]	8.13 ± .29[e]	1.58±.02[c]	1.56±.04[c]

[c,d,e] Means in the same row that do not have a common superscript differ (P<0.05).
From Lee and Ashmore (1985)

It can be concluded that heat shortening must have caused toughening of the feedlot+HT sides and that tenderness did not improve with aging. Sarcomere length of grass-fed sides were not different at any chilled treatment, indicating that cold shortening occurred because of light carcass weight (236.6 kg) and low backfat thickness (0.36 cm).

These studies support the indication that subcutaneous fat deposition may be closely associated with beef palatability. Bowling et al (1977), explained that the insulatory effects of moderate levels of subcutaneous fat reduce the rate of carcass temperature decline during post-mortem chilling and improve beef tenderness by lessening the extent of cold induced toughening and by enhancing the rate of post-mortem muscle autolysis. It seems to be logical to consider subcutaneous fat thickness in combination with marbling to achieve more equitable stratification of beef carcasses according to the degree of palatability.

Tatum et al. (1982) studied the effects of stratified subcutaneous fat thickness on tenderness. Rib steaks from carcasses with ≥ 5.08 mm of fat thickness had lower WBSF values and higher sensory panel trained (SPT) scores than those with ≤ 5.08 mm, but rib steaks with fat thickness ≥ 7.62 mm did not show an advantage (Table 2.2). These steaks were classified by panelists as desirable or undesirable tender. Carcass with ≥ 7.62 mm fat thickness had an advantage compared to those with 5.08-7.61 mm or those with ≤ 5.08 mm. When this classification was crossed with marbling, higher percentage of steaks from carcasses with ≥ 7.62 mm and slight marbling were evaluated more desirable than steaks from carcasses with ≤ 7.61 mm.

Table 2.2 Least squares means for overall tenderness and shear force according to subcutaneous fat thickness group

Subcutaneous fat thickness	No. observations	Overall tenderness	Shear force (kg)
2.54 to 5.07 mm	12	5.21[e]	5.02 [d]
5.08 to 7.61 mm	73	5.77[d]	4.31 [e]
7.62 to 10.15 mm	102	5.78 [d]	4.31 [e]
10.16 to 12.69 mm	98	5.84 [d]	4.27 [e]

[d,e,f] Means in the same column that do not have a common superscript differ (P<0.05).
Adapted from Tatum et al. (1982)

Dolezal et al. (1982) studying the effects of days-on-feed and subcutaneous fat thickness on steer rib steak tenderness, found improvements in this attribute (7.82[g], 6.13[f] and 4.85[e], respectively, P<0.05), as the fat thickness increased from ≤ 2.53 mm, ≥ 2.54 to ≤ 5.07 mm and ≥ 5.08 to ≤ 7.61 mm kg. However, they did not find improvements for carcasses with ≥ 7.62 to ≤ 10.15 mm (4.60[de] kg) and above. The authors stated that classifying carcasses based on these three levels of fat thickness (< 5.0 mm; 5.0 to 9.9 mm and > 10 mm) was equivalent to the use of USDA quality grades to sort carcasses according to expected palatability.

With the goal of including a minimum adjusted fat thickness requirement of 5mm to the USDA beef quality grading standards for Select grade, Shackelford et al (1994a) showed that WBSF values were higher (5.58 vs. 5.32 kg, P<0.01) and trained sensory panel tenderness (TSPT) was lower (4.82 vs. 4.99, P<0.01) for carcasses with < 5mm subcutaneous fat thickness compared with those with ≥ 5mm, within a slight amount of marbling (Select). However, the authors concluded that the differences in WBSF and TSPT were small and that the addition of ≥ 5mm fat thickness for the Select grade would not improve tenderness significantly.

In the last three studies, pH and temperature decline information was not obtained to determine if cold shortening occurred in any of these carcasses.

With this purpose, Jones and Tatum (1994) relating fat thickness, marbling, pH and temperature at 3-hr post-mortem to tenderness found that U.S. Select carcasses with ≥ 5 mm fat thickness had a higher mean TSPT score (5.26) and lower WBSF (2.70 kg) than U.S. Select carcasses with < 5 mm of fat thickness (4.5 and 3.05 kg respectively, $P<0.05$). For U.S. Choice carcasses, adding a minimum of ≥ 5 mm of fat thickness decreased WBSF from 2.68 to 2.42 kg ($P<0.05$) but did not improve TSPT score (5.31 vs. 5.33). In contrast with the conclusions of Shackelford et al (1994a), these authors concluded that at least 5 mm fat thickness would improve average tenderness and reduce tenderness variation in Select grade carcasses.

A reduction in the quantity of carcass fat in meat producing animals is desirable for economic reasons. Fat deposition requires more energy than protein deposition and some of the extra fat is removed from the carcasses at processing; however, a minimal amount of fat may be desirable to improve meat quality. Subcutaneous fat may insulate the carcass and lead to slower post-mortem chilling, which may, in turn, improve tenderness by reducing cold shortening. Feeding cattle to a minimum of 5mm subcutaneous fat to slaughter is not antagonistic to efficient beef production, since some researchers (Ferrell et al., 1996) considered that a certain level of body condition is necessary for optimal reproductive efficiency. A body condition score of 5 corresponds to 5mm of rib fat cover. From the research, it can be inferred that subcutaneous fat only adds a slight assurance of acceptable tenderness when the control of other variables is unknown.

Effect of marbling on meat tenderness

Marbling or intramuscular fat deposition is one component of the USDA quality grade system, and many studies have related marbling to tenderness. The literature leave as is that marbling accounts for 5 - 10% of beef palatability variation. The contribution of increased marbling in improving tenderness of meat is through its effects in: decreasing bulk density; causing strain within layers of connective tissue; providing lubrication of the protein fractions of meat and providing insurance against the effects of overcooking. Fat depots distributed throughout a section of meat make it more tender because fat globules are less resistant to shear force than are muscles fibers and connective tissue, because the brain's perception of tenderness is tempered by the juiciness

contribution of fat; because straining of connective tissue by fat deposits makes collagen more susceptible to gelatinization, and because the fat surrounding the muscles fibers decreases the extent of protein coagulation during the cooking process at higher degrees of doneness. The greater the dispersion of the marbling deposits throughout the muscle, the greater the likelihood that the effects of marbling on tenderness occur during cooking and/or chewing.

Shackelford et al. (1994b) in studying 1,602 steers of different cattle types found that WBSF values decreased ($P<0.05$) with the levels of marbling from ≤ traces, slight, small and ≥ modest (6.06, 5.45, 4.82. 4.28, respectively) and TSPT increased ($P<0.05$) with the same levels (4.64, 4.90, 5.21, 5.41, respectively). Similar results also were obtained with determination of TSP juiciness.

Wheeler et al. (1994), evaluating steers and heifers from the germplasm evaluation research project at the U.S. Meat Animal Research Center, found similar decreases in WBSF values ($P<0.05$) as marbling increased from traces to slight to small, but did not decrease further as marbling increased. However, the variability in WBSF decreased as marbling increased to higher levels.

Jones and Tatum (1994) concluded that slight plus and small marbling scores resulted in similar rib eye tenderness (WBS: 2.72 vs. 2.50 kg; TSPT: 5.20 vs. 5.28, respectively). In this study marbling accounted for 9% of the WBSF variation and 5.1% of TSPT variation.

Huffhines et al. (1992) segregating 398 rib steaks by percentage of intramuscular fat reported that the overall palatability ratings increased along the percentage of lipids (Table 2.3).

Table 2.3 Means for overall palatability ratings according to intramuscular fat group

Intramuscular fat %	Overall palatability
< 2.00%	5.39[c]
2.00 to 2.99 %	5.54[c]
3.00 to 3.99 %	5.58[bc]
4.00 to 4.99 %	5.73[ab]
5.00 to 5.99%	5.75[ab]
> 6.00 %	5.84[a]

[a,b,c] Means in the same column that do not have a common superscript differ ($P<0.05$).
Adapted from Huffhines et al. (1992)

Smith et al. (1984) conducted another study on the relationship between marbling and tenderness. They collected information from 1,005 carcasses of A and B maturity. Within A maturity carcasses, no significant differences occurred in WBSF and SPT between slight and small (5.88 vs. 6.01, respectively). When A and B maturity carcasses were combined, overall palatability (OP) was higher ($P<0.05$) for carcasses with small marbling compared to those with slight. With higher levels of marbling, carcasses with ≥ modest marbling were more tender ($P<0.05$) compared to those with small marbling. This finding is concordant with that of Shackelford et al. (1994b), but disagrees with the results of Wheeler et al. (1994).

Wulf et al. (1996) studying three subprimal cuts (strip loin, top sirloin and top round) coming from 114 steers did not find any correlation ($P>0.05$) between marbling score and shear force, but they did observe a negative one ($P<0.05$) with taste panel tenderness across all cuts ($r=-0.11$). This negative relationship was explained by a decrease in tenderness as the animal age increased and an increase in marbling scores with the age.

In a Beef Customer Satisfaction study (NLSMB, 1995) consumers evaluated strip loin steaks from low and high Select and low and top Choice. The steaks from low Choice had higher ($P<0.05$) tenderness scores than the steaks from low Select (6.6 vs. 6.5), meanwhile steaks from top Choice had higher scores ($P<0.05$) compared to those from low and high Select (6.8 vs. 6.5 and 6.6 respectively).

The WBSF data showed that low and top Choice strip loin steaks were more tender ($P<0.05$) than those coming from low and high Select (2.60 and 2.57 kg vs. 2.74 and 2.75 kg, respectively). For this subprimal cut, increased marbling resulted in higher SPT. Savell and Cross (1986), cited by Dikeman (1996) proposed that minimum intramuscular fat of 3% is essential for acceptable palatability. This percentage corresponds to a minimum slight marbling or Select grade. However, other authors have concluded that 3% of lipid is questionable for palatability acceptance, since palatability decrease significantly as in lipid decreased from 3.5% to 2.5%.

Abundant research about this variable has concluded that marbling is a poor predictor of tenderness, although degree of marbling accounts for a low percentage of tenderness variation (5-9%).

Tenderness and physiological or chronological age

Because tenderness is consistently lower for mature than for growing cattle, carcass maturity scores have been emphasized in USDA carcass grades attempting to satisfy the consumer demand for uniform and palatable products. This is based on the fact that older animals have proportionally more connective tissue in their muscles and more cross-linkages in the collagen and reticulin fibrils of their connective tissues than do younger animals. As a result, the meat from older animals and mature carcasses is usually less tender compared with meat from younger animals and youthful carcasses.

Several comprehensive reviews of collagen crosslink biosynthesis have been published. Because the primary collagen phenotypes in perimysial collagen are types I and III, most of these reviews address the mechanisms of crosslink formation that occur in these forms. The vast bulk of the intramuscular connective tissue is perimysium, and it is thought that it plays the major role in determining meat texture differences (Light et al., 1985). Crosslinking is initiated immediately upon fibril aggregation by the oxidative deamination of specific lysine or hydroxylysine residues by the lysyl oxidase enzyme. Lysine and hydroxylysine derived aldehydes result (allysine and hydroxyallysine, respectively). There are two pathways to form crosslinks: 1) the allysine pathway that produces aldimine crosslinks and 2) the hydroxyallysine path resulting in ketoamine crosslinks.

The initial condensation products form reducible crosslinks because they contain Schiff-base double bonds, which can be reduced. These crosslinks link only two collagen molecules together. These divalent crosslinks tend to disappear with time and are replaced by mature, nonreducible crosslinks. The mature crosslinks on the hydroxyallysine pathway are trivalent, hydroxylysylpyridinium (HP - heat stable) and lysylpyridinium residues. The progression of crosslinks from divalent to trivalent increases the strength of intramuscular connective tissue matrix. The progressive nature of crosslink biosynthesis does not mean that there is always a steady, irreversible shift of immature to mature forms.

Although there generally is an increase in mature connective tissue crosslinks with chronological age, it is also clear that the rate of crosslink formation and directional shifts in the concentration of mature crosslinks, regardless of age, can be altered. In skeletal muscle reducible crosslinks are rapidly replaced with mature forms. For example, by 1 year of age in steers, the concentration of HP is twofold greater than its precursor. Also the HP concentrations vary with the different muscles. The *longissimus dorsi* muscle, which has an acceptable tenderness, possesses less collagen and crosslinked collagen than *biceps femoris* or *semimembranosus*. The review concluded that mature crosslinks and collagen concentration have an additive effect on the toughening of meat (McCormick, 1999).

Some discrepancies do exist about the accuracy of sorting beef carcasses into age groups using the current USDA method of subjectively evaluating skeletal and lean maturity. Other countries such as Uruguay and Australia use the number of permanent incisors present at slaughter to estimate maturity in their beef carcass classification systems (INAC, 1997; AUS-MEAT, 1995). Both systems consist of dentition age grades: zero, two, four, six and eight teeth, considering a pair of teeth to have erupted when the first tooth of the pair penetrated the gum. Lawrence et al. (2001a) comparing the USDA bone ossification/lean based maturity system with a dentition based maturity system, found that determining physiological maturity by number of permanent incisors rather than by the current USDA method may prove to be more accurate to sort carcasses into less variable age.

This study showed that 91.5 to 100% of 0-teeth cattle (<23.8 mo. of age), 89.1 to 97.5% of 2-teeth cattle (23.8 to 30.4 mo. of age), 75 to 82.2% of 4-teeth cattle (30.4 to 38 mo. of age), 64 to 72.5% of 6-teeth cattle (38 to 45.3 mo. of age) and 40% of 8-teeth cattle (>45.3 mo. of age) were graded as A maturity by the USDA system.

Field et al. (1997) studying heifers of two degrees of maturity (A and C), did not detect any difference in collagen percentage in bone between A and C maturity. Previous work of Field et al. (1974) found similar hydroxyproline levels in bone from cattle 2 to 96 mo. of age. In muscle, neither collagen percentage nor HP concentration varied between maturity grades.

Correlating overall bone maturity scores and HP in muscle, the coefficient of correlation was low (r=0.04). This could be explained by the collagen maturation process in bone and muscle, where both processes occur independently. Within the age of cattle in this study, maturation of collagen in muscle was not related to bone maturity. No significant differences (P>0.05) were detected for panel tenderness scores and WBSF values between A and C maturity carcasses. The authors concluded that differences in bone maturity are of limited value to predict eating quality and more direct measures of beef tenderness are needed to reduce variability. According to this last conclusion, Owens and Gardner (1999) reported in a trial summary that shear force increased with chronological age at harvest, however maturity indices based on visual appraisal of lean and bone were not significant.

Hilton et al. (1998), in 354 fed (steers and heifers) and non-fed (cows) animals including five skeletal maturity classifications (A to E), reported a decreased tenderness and an increased WBSF with the increased carcass maturity (Table 2.4). These results allowed the conclusion that the methodology used to assign USDA maturity scores of beef carcasses were effective for grouping carcasses according to differences in tenderness and overall palatability.

Table 2.4 Means showing the effect of overall carcass maturity classification on beef tenderness

	Maturity classification				
Trait	A	B	C	D	E
Shear force	2.56^{k}	2.69^{jk}	2.82^{j}	3.06^{I}	3.53^{h}
Overall tenderness	5.34^{h}	5.19^{h}	4.65^{I}	4.24^{j}	3.60^{k}

^{h,i,j,k} Means in the same row that do not have a common superscript differ (P<0.05).
Adapted from Hilton et al. (1998)

Wulf et al. (1996) found that animal age was positively correlated (P<0.05) with marbling but it was not correlated (P>0.05) with 24-h calpastatin activity (r=0.02). Animal age was positively correlated with shear force across all the cuts (striploin r=0.12, top sirloin r=0.26, top round r=0.16). They also showed a negative correlation (P<0.05) between animal age and sensory panel tenderness for all beef cuts measured (r=-0.24). The data in this study indicated a decrease in tenderness with the age, especially in high-collagen cuts, in a narrow range of maturity (15-18 months of age).

Lawrence et al (2001b), selecting 200 carcasses by dental classification and USDA maturity system, did not find significant differences in WBS force and sensory panel tenderness among the five dental classes or among USDA maturity scores A, B, and C. These results agree with Wyhtes and Shorthose (1991) who reported no difference in *longissimus* shear force among dentition groups and support the concept that classification of carcasses based on dentition should not be used in place of USDA carcass maturity to segregate carcasses for *longissimus* steak tenderness.

Research based on the relationship between cattle maturity and beef tenderness/palatability has been contradictory and inconsistent. Although it seems that dentition is a more accurate and objective measure of carcass maturity, there is no evidence to suggest that dentition is more effective than USDA skeletal ossification /lean maturity system in predicting lean palatability.

Effect of the rate of pH decline and the rate of cooling

The properties of meat that are of most interest to the consumer are strongly affected by perimortem treatments: the physical conditions that are imposed on the animal in the last few days of life and on the carcass in the first few hours post-mortem. The effects of these treatments are exerted through anaerobic glycolysis, the post-mortem breakdown of glycogen to lactic acid. According to Bendall (1973), the rate of pH decline is determined by the rate of adenosine triphosphate (ATP) turnover and so the variability in the former rate is likely to be due to varying intracellular free-calcium levels exerting a stimulating effect on the actomyosin ATPase. The rate of the breakdown of ATP determines the rate of post-mortem glycolysis. Phosphofructokinase and to a lesser extent, phosphorylase play the major role in the control of glycolytic metabolic levels (Bendall, 1973). Considerable variations in glycolysis may occur between animals and also between separate locations within a beef carcass. According to Kauffman and Marsh (1987), glycolytic rate in the first few hours following slaughter is a major determinant of quality. The pre-rigor muscle environment is critical in determining the behavior of myofibrillar proteins and their subsequent impact on meat quality attributes such as tenderness, texture, drip loss, color and color stability.

The extent of glycolysis is a powerful influence on several meat qualities but the rate of glycolysis is a major determinant of tenderness through its effect on temperature and pH and, hence, its influence on proteolytic enzyme activity (Marsh, 1993).

The two main determinants in defining the pre-rigor conditions are the rate of pH fall and the rate of cooling. These two variables are obviously not independent as temperature will affect pH decline, but pH decline can also be manipulated independently by the level of electrical inputs applied to the carcass. Electrical inputs extend from electrical stunning, used to either kill the animal or render it unconscious prior to neck cutting to the various forms of electrical immobilization and stimulation that occur during and after the dressing procedures.

Tatum et al. (1999) developed a total quality management (TQM) approach to meat quality. The TQM consists in identifying critical control points (CCPs) from the production, pre-slaughter, processing and value-adding sectors of the beef supply chain and quantified their relative importance in reducing the incidence of tough beef. The Meat Standard of Australia (MSA) also adopted a TQM approach to identify CCPs and predict the quality of the final product. The key to defining practical and effective processing options is to understand the limits at which eating quality becomes compromised by other commercial requirements. The level of tenderness or toughness in meat is due to two features of the post-mortem muscle: a) the degree of sarcomere shortening and b) the level of proteolytic activity.

One of initial specifications for the MSA carcass-grading scheme is the pH/temperature window (Fig.2.1). The concept of the window showed that myofibrillar shortening occurred when pre-rigor muscle was held at either low or high temperatures. Locker and Hagyard (1963) demonstrated that temperature after slaughter was important and now is accepted that the minimum contraction occurs at 15^{o}C. Pearson and Young (1989) considered that for cold shortening to occur, the muscle pH had to be greater than 6.0, with ATP still available for muscle contraction and the muscle temperature to be less than 10^{o}C. Precisely why the muscle contracts under the influence of low temperature is not known. Bailey (1972) considered that the contraction of the muscle is probably triggered by the release of Ca^{2+} ions from the sarcoplasmic reticulum.

Marsh (1977) mentioned an alternative hypothesis where the free calcium initiating cold shortening comes from the mitochondria responding to post-mortem anoxia and not from the sarcoplasmic reticulum reacting to the cold. Shortening between 20-40% of the sarcomere length produces severe toughening and this persists throughout aging (Davey and Gilbert, 1973). At high muscle temperatures some shortening also occurred in some cases leading to increased toughness. This effect was termed heat shortening and was considered to be due to the combination of high temperature and low pH in the muscle causing early exhaustion of proteolytic activity (Dransfield, 1993)

The other effect of the pH and temperature in pre-rigor is related to the activity of enzymes involved in regulating the conversion of glycogen to lactic acid which lowers meat pH and in breaking muscle myofibrillar proteins.

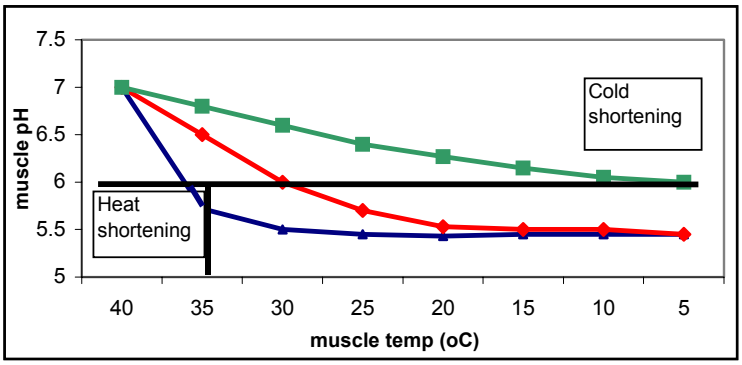

Fig. 2.1 The pH/temperature window used by MSA to optimize the decline in pH relative to the temperature of the muscle. Adapted from Thompson (2002)

Hwang and Thompson (2001a) examined the effect of applying stimulation either immediately after slaughter or just prior to entry into the chiller on glycolytic rate, protease activity, and subsequent meat quality. They confirmed that early application of stimulation was associated with a very rapid decline in pH, which led to exhaustion of the protease system (lower μ-calpain and higher calpastatin activities) and higher peak shear force. The detrimental effect of rapid glycolysis on tenderness supported earlier studies showing meat toughness resulting from a high rigor temperature. At the other extreme, tough meat from non-stimulated sides with a slow rate of glycolysis appeared to

be associated with a delayed activation of the calpain system. Smulders et al. (1990), studying the relationship between glycolytic rate and sarcomere length, concluded that tenderness is very highly dependent on shortening in slow-glycolysing muscles, but it is completely independent of it in muscles of more rapid pH decline.

In a subsequent study, the authors Hwang and Thompson (2001b) studied a combination of stimulation and chilling treatments to cause independent variation in pH and temperature decline. The results showed that the rate of pH decline had the largest effect on eating quality. They found a significant $pH_{1.5}$ x $temperature_{1.5}$ interactions ($P<0.05$) on the μ-calpain and calpastatin at 24 h post-mortem. In rapidly chilled sides, μ-calpain and calpastatin activities at 24 h post-mortem were independent of the rate of pH fall. However, in slowly chilling sides an increase in the rate of glycolysis resulted in a linear decrease in both enzyme activities at 24 h post-mortem. The optimum pH decline to produce the tenderest meat was dependent on the days of aging. Striploins which had a rapid decline in pH showed a smaller decrease in shear force with aging, compared with carcasses with a much slower rate of pH fall. In this study and under experimental conditions an intermediate pH decline (pH 5.9-6.2 at 1.5 h post-mortem) or a temperature of 29-30^{o}C at pH 6 produced the most tender meat in striploins after 14 days of aging. In a different time of pH measuring, Smulders et al. (1990, observed that the pH range (5.9-6.1) at 3 h (pH_3) post-mortem allowed attaining the highest value of sensory panel tenderness and also coincided with the glycolysis rate that produced the longest sarcomeres. In the same study, they concluded that sarcomere length was highly related ($r=0.84$) to tenderness rating in slow-glycolysing ($pH_3>6.3$) beef loins but there was low correlation ($r=0.16$) between both variables in fast-glycolysing loins. Marsh et al. (1987) had demonstrated that carcasses at an intermediate rate of post-mortem pH decline ($pH_3= 5.9 - 6.3$) produced more tender meat than fast and slow glycolysing carcasses. O'Halloran et al. (1997) also reported that the fast glycolysis group (pH_3 5.94) was rated significantly more tender ($P<0.001$) by sensory panel with 7 days of aging (slow glycolysis: 4.24 vs. fast glycolysis: 6.22). This is in agreement with the results presented by Marsh et al. (1987), Smulders et al. (1990), and Pike et al. (1993). However, O'Halloran et al. (1997) did not find any correlation between sarcomere length and tenderness at 2, 7 or 14 days post-mortem.

Marshall and Tatum (1991) cited by Shackelford et al. (1994c) tested the efficacy of pH_3 to predict beef palatability in commercial packing plants and obtained the most tender beef when pH_3 was below 5.8. In Marshall and Tatum (1991) study, as in the Shackelford et al. (1994c) research, pH_3 was not highly correlated with tenderness (r=0.16 and 0.03, respectively) and it was not effective in grouping carcasses by tenderness. In the former work, the authors did not find differences between three groups of pH_3 (<6.0; 6.0 to 6.4; >6.4) for mean shear forces values (5.58, 5.55 and 5.78 kg, respectively) and sarcomere length (1.91, 1.82 and 1.82 μm, respectively). Jones and Tatum (1994) reported a significant ($P<0.01$) correlation between pH_3 and WBSF (r=0.16). They divided into three pH_3 sub-groups: low pH_3 < 6.2; intermediate pH_3 = 6.2 to 6.46 and high pH_3 > 6.46 and detected WBSF differences between low and high pH_3 groups ($P<0.05$). The WBSF obtained in this study were 2.43 kg, 2.65 kg and 2.83 kg for low, intermediate and high pH_3 groups, respectively. The mean differences in tenderness were small and of questionable practical importance. Additionally, the frequency of steaks with shear force values of 3.9 kg or higher decreased as pH_3 decreased ($P<0.05$). However, in this study, pH_3 accounted for less than 3% of the variation in WBSF.

Lochner et al. (1980) reported that tenderness was highly dependent on early post-mortem temperature, but their experiment confounded feeding-regime with temperature differences, creating difficulty in determining which variable affected the differences in tenderness. Shackelford et al. (1994c) observed no relationship (r=0.06) between temperature at 3 hr ($temp_3$=24.06 ^{o}C) and WBSF (5.61 kg).

May et al. (1992) and Lochner et al. (1980) reported that, the temperature of the *longissimus* muscle measured at 2 to 4 h post-mortem was the trait most closely correlated with tenderness. Lochner et al. (1980) obtained a high correlation (r=0.78) between temperature at 2 h post-mortem and sensory panel ratings for tenderness.

May et al. (1992) reported moderate correlations of *longissimus* temperature at 2.5 h post-mortem with WBSF (r=-0.63). However, Jones and Tatum (1994) did not find any correlation ($P<0.05$) between any post-mortem *longissimus* temperature (measured at 1, 3, 6, 9, 12, and 24 h post-mortem) and WBSF or SPT.

Pike et al. (1993) supported the hypothesis that the glycolytic rate is the most important post-mortem factor in beef tenderness and their results are compatible with the view that early post-mortem temperatures influence tenderness mostly through their control of glycolytic rate. They also recommended an intermediate rate of glycolysis (pH_3= 6) to produce optimum tenderness. In this study, quadratic equations utilizing pH at 3 h gave the best estimate of WBSF for 2, 4, 8 and 16 days steaks.

Muscle pH and temperature interact continuously during rigor development as they impact on both physical shortening and proteolytic enzyme activity. Partially contradictory results were noted from these studies, but they supported the notion that the rate of pH decline had the largest effect on eating quality. Evidence is accumulating that a curvilinear relationship exists between early post-mortem pH and tenderness (Hwang and Thompson, 2001b; Pike et al., 1993; Marsh et al., 1987). Intermediate pH decline (pH_3= 5.9-6.2) or a temperature of 29-30^{o}C at pH 6 produced the most tender meat and the longest sarcomeres.

Impact of ultimate pH on tenderness

The management of the ultimate pH (pH_u) of meat is an important component of controlling the quality and consistency of meat products. The grading scheme called Meat Standards Australia (MSA) implemented by the Meat and Livestock Australia (MLA) and the New Zealand Beef and Lamb Quality Mark from the New Zealand Meat Board have included the ultimate pH measured in the *longissimus dorsi* as a specification for quality meat for their domestic market. For the MSA, all carcasses must have an ultimate pH below 5.7 at 18-24 hours post- mortem. Meat with a final pH value greater than 5.7 is less tender and darker than meat with a final pH value less than 5.7. According to the consumer taste panels, 20% of steaks with pH< 5.7, 41% of them in the range of 5.7-5.8 and 54% of the steaks with pH > 5.8 were graded as unsatisfactory (Thompson, 2002). The New Zealand Quality Mark excludes beef carcasses with an ultimate pH > 5.8 (Simmons et al., 2000).

Wulf and Page (2000) found that carcasses with muscle pH values of 5.45 or less had more tender *longissimus* steaks compared with those with muscle pH values greater than 5.45 (Table 2.5) demostrating a strong relationship between variables within a narrow pH range of 5.3 to 5.5. They concluded that muscle pH appears to be useful at distinguishing a group of carcasses that have especially tender *longissimus* steaks. An improvement in beef tenderness could be achieved by lowering muscle pH with new pre or post slaughter technologies. However, Wulf et al. (1997) found a substantial variation in tenderness with a range in shear force values from 1.46 to 5.16 kg and a range in taste panel tenderness ratings of 3.57 to 7.21 in muscle pH_u range from 5.35 to 5.79.

Table 2.5 Effect of muscle pH on beef tenderness

	Muscle pH				
Variable	<5.41	5.41 to 5.45	5.46 to 5.50	5.51 to 5.70	> 5.70
Shear force kg	2.96[x]	3.73 [x]	4.46[y]	4.66 [y]	4.99 [y]
Tenderness[a]	7.05 [x]	6.44 [x]	5.67 [y]	5.64 [y]	5.43 [y]

[a] Taste panel ratings 8= extremely tender, juicy, intense, desirable; 1= extremely tough, dry, bland, undesirable
[x,y] Least-squares means within a row lacking a common superscript letter differ (P<0.05)
Adapted from Wulf and Page (2000)

The high ultimate pH of meat, as a consequence of depleted muscular glycogen reserves prior to slaughter, greatly affects meat quality. Various stress factors have been mentioned as responsible for glycogen depletion: time and manner of transportation of animals from the farm to the abattoir, diet restrictions, mixing animals of different lots, lairage time, climatic factors, pathological conditions, and genetic factors. These deleterious effects may be exacerbated in individual animals with poor temperament.

In practice, any situation which provokes a substantial depletion of muscle glycogen reserves will give rise to meat with a high ultimate pH if the animal is slaughtered before its energetic reserves are restored (Tarrant, 1981). High concentrations of muscle glycogen immediately pre-slaughter are critical for the effective conversion of muscle into tender quality meat.

The relationship between ultimate pH and tenderness is, however, controversial. Some authors (Bouton et al., 1973; Guignot et al., 1994; Silva et al., 1999) found a linear relationship between these two parameters. Others (Purchas, 1990; Jeremiah et al., 1991; Purchas and Aungsupakorn, 1993; Wulf et al., 1997) however, found a curvilinear relationship with minimum tenderness between 5.8 and 6.2 pH values. Several hypotheses have been proposed to explain this curvilinear relationship, and the reasons have not been adequately explained. Yu and Lee (1986) suggested a differential proteolytic activity was responsible for the toughness of meat of pH 5.8-6.3. There is less activity of these enzymes at intermediate final pH values because this range lies outside the pH optima of two separate enzyme systems. Thus, the increasing tenderness found as the ultimate pH rises from 6 to 7 is attributed to greater calpain activity, which is maximal at neutral pH. In contrast, the increasing tenderness as final pH falls below 6.0 has been attributed to enhanced acidic protease activity (cathepsin). At intermediate pH values, the pH is neither optimal neither for calpains nor for cathepsin activity, resulting in the lowest degree of meat tenderization during aging. It has been suggested that the lysosomal enzyme activity may be responsible for the tenderization process as the pH falls from 6 to 5.4 since their pH optima are found in these lower ranges, but significant evidence has been accumulated which demonstrates that post-mortem tenderization is Ca^{2+}-(Koohmaraie et al., 1988) and calpain-dependent (Koohmaraie, 1990; Dransfield, 1993), while inhibition of lysosomal enzyme activity has little effect on tenderness, even when ultimate pH is in the normal low range (Koohmaraie et al., 1988).

Watanabe et al., (1996) and Koohmaraie, (1990) demonstrated the absence of tenderization following $ZnCl_2$ injection into the *longissimus dorsi* and attributed it to inhibition of calpain activity with no evidence that $ZnCl_2$ has any effect on lysosomal enzymes. Without any obvious justification for invoking lysosomal involvement, the explanation for the resurgence in aging rate as the final pH falls below 6.0 becomes difficult to explain.

Non-enzymatic mechanisms also have been proposed. Takahashi (1996) states that many meat tenderness changes can be explained by the direct effect of calcium on myofibrillar proteins and that this effect is pH-dependent with a minimum effect at pH 6.5.

Reduced sarcomere length is recognised as an important cause of increased toughness in meat. Purchas (1990) and Purchas and Aungsupakorn (1993) have suggested that the decrease in sarcomere length as pH increases to 6.2 may partially explain the higher levels of toughness of intermediate pH meat (1.64 μm for pH 5.5 to 1.51 μm for pH 6.2). Watanabe et al. (1996) reported that the explanation for increased toughness at intermediate ultimate pH may therefore derive from sources other than calpain proteolysis. This is at least suggested by the effects of the final pH on the myofibrillar fragmentation index. This index provides an alternative measure of the tenderization process and measures the extent of aging through changes in the fragility of the myofibrils that proceeds from the weakening of Z-line proteins. It gives a more direct measure of aging than shear force measurements of cooked samples since it avoids the confounding effects of the cooking process. These authors working with lambs found a curvilinear relationship between final pH and shear force values with a toughness peak at 6.07. When they used the myofibrillar fragmentation index to measure aging there was a minimum effect around pH 6.4 indicating that factors other that proteolysis may also be implicated. These findings are supported by Purchas et al. (1999) who suggested that the greater toughness of beef at intermediate pH might be explained by other factors involved than degree of muscle fiber contraction and extent of myofibrillar protein breakdown.

In this study, and in contrast with previous work (Purchas, 1990), sarcomere length did not decrease as final pH increased from 5.5 to 6. Also contradictory with the results of Watanabe et al. (1996), Purchas et al. (1999) found a maximum myofibrillar fragmentation index at ultimate pH values greater than 6.5. Shackelford et al. (1991) reported very low correlation between pH_u and MFI measured at 1, 3, 7, 14 days of aging in beef *longissimus thoracis*, but the variation in pH_u was also low. Silva et al. (1999) observed that MFI was more dependent on the period of aging than on pH_u.

Effects of cooking on tenderness

The cooking temperature of meat also appears to influence the relationship between ultimate pH and tenderness. In raw meat, tenderness is not related to pH (Dransfield, 1981), at medium cooking temperatures (65^{o}C) the relationship is curvilinear and at high temperatures (90^{o}C) it is linear (Bouton et al., 1971).

This effect of temperature on meat tenderness may result from the effect of cooking on water holding capacity (Purchas, 1990) or on the connective tissue (Dransfiel, 1994). However, some discrepancies exist among different studies in the relationship between the final pH and the ultimate tenderness measured objectively (WBSF) or subjectively (SPT) cooking the samples to an internal temperature of 70^{o}C. Purchas (1990) and Purchas et al. (1999) in a curvilinear response between variables (pH_u and WBSF), considered that from a practical point of view the decreasing tenderness as the ultimate pH increases from 5.5 o 6.2 it is probably of most concern. However, Silva et al (1999) found a negative linear relationship between final pH and WBSF ($r= -0.83$ to -0.70, $P<0.01$) and a positive relationship between SPT and pH_u ($r= 0.81$ to 0.71, $P<0.01$) for different aging periods (1, 6 and 13 days).

Using the final pH as criteria to predict tenderness, Purchas (1990) found that 55% of the shear force variation was explained by pH, while 50% was accounted for by sarcomere length alone for the samples with pH values less than 6.2 and 7 days of aging.

When these independent variables were combined in the same regression equation, only 66% of the WBSF variation was explained suggesting that the effect of pH on shear values was mediated, at least in part, through an effect on sarcomere length. In a different study, Purchas et al. (1999) showed that the percentage of variation in peak shear force that was accounted for by final pH was 58% and 49% for the samples aged 1 and 20 days, respectively. Meanwhile, the sarcomere length only explained 4 to 5.6% of this WBSF variation, for 1 and 20-days of aging respectively.

Some researches have shown low coefficients of determination (R^2) from regression equations using pH as an independent variable. Wulf et al. (1997) reported that pH explained only 12% of the WBSF variation.

In data collected on 3,435 beef carcasses over a ten-year period, Jeremiah et al. (1991) reported that 0 to 22% percent of the variation in shear force was accounted for the ultimate pH in all years. When this information was analyzed by sex group the final pH accounted for a relatively large amount of the variation in shear forces values only in bulls, known to be more susceptible to ante-mortem stress.

The results support previous conclusions that muscle pH was not a useful predictor of tenderness in the absence of ante-mortem stress factors.

The literature showed contradictory results in the relationship between final pH and ultimate tenderness of the product (*longissimus dorsi*). Within a normal ultimate pH range (5.4-5.7) results show that lower pH_u is associated with an improved level of tenderness (Wulf and Page, 2000; Thompson 2002). In a quadratic response, where stress factors can be involved giving more variation in the final pH, the decreasing tenderness as the ultimate pH increases from 5.5 o 6.2 is probably of most concern from a practical point of view.

Segregating beef carcasses with ultimate *longissimus* pH values between 5.8 and 6.2 appears to be a nondestructive means to effectively segregate tough carcasses. In practice, this principle is applied by the Meat Standard of Australia and the New Zealand Beef and Lamb Quality Mark for their domestic market.

Meat color and its relationship with ultimate pH and tenderness

The acceptability of beef after purchase is determined almost exclusively by the satisfaction derived from its consumption. As beef is merchandized at retail, consumers evaluate several factors when selecting a cut. The visual appraisal of meat products can determine whether or not a consumer will make a purchase. Hedrick et al. (1994) stated that one of the most important factors in the selection of a meat product is color, and Abril et al. (2001) suggested that the first criterion utilized by the consumers to judge meat quality, freshness and acceptability is meat color.

Color measurements followed the CIE color convention (CIE, 1986) where the three fundamental outputs are L*, a* and b*. L* is the lightness on a scale of 0 (all light absorbed) to 100 (all light reflected); a* spans from + 60 (red) to – 60 (green) and b* spans from + 60 (yellow) to – 60 (blue).

Color is mainly influenced by the myoglobin (Mb) content and nature, the composition and physical state of muscle (Renerre, 1990) and the meat structure. The latter is directly related to the

ultimate pH and several researchers have demonstrated a relationship between meat tenderness and ultimate muscle pH (Purchas, 1990; Watanabe et al., 1996) and muscle color (Jeremiah et al., 1991; Wulf et al.,1997). Furthermore, when quality-grading beef carcasses, trained USDA personnel evaluate muscle color as related to carcass maturity and muscle pH when determining quality grades (USDA, 1997). Wulf et al. (1997) reported that the three colorimeter values (L*, a* and b*) were intercorrelated, however, the authors considered that a* is probably more useful than b* when measuring beef color stability over time because a* could be associated to metmyoglobin formation since the color of beef changes from red to green as it is stored fresh.

Mb pigment content is intrinsic to the muscle and varies with production factors such as species, breed, animal age, sex, muscle type or feeding system. Other extrinsic factors also affect color development such as pre-slaughter conditions, electrical stimulation, chilling, and oxygenation and oxidation processes during aging. These factors either act directly on the myoglobin or indirectly change the pH and its rate of decline. The impact of different processing conditions (fast vs. slow processing) is of particular importance in giving meat the desired appearance. Boakye et al. (1996) found that chilling rate and fat thickness affected L* and b* (Table 2.6).

Table 2.6 Correlations between color parameters and chilling rate and fat thickness

Color parameters	Chilling rate	Fat thickness
L*	0.40	0.39
b*	0.32	0.33

Correlations $P<0.01$
Adapted from Boakye et al. (1996)

Meat color is determined by the relative amount of three myoglobin derivatives, a) reduced myoglobin, deoxymyoglobin (Mb), which is the purple pigment of deep muscle, b) oxygenated myoglobin, oxymyoglobin (MbO_2), which is bright cherry red and results from muscle exposure to oxygen, producing the familiar “bloom” of fresh meat, and c) oxidized myoglobin, metmyoglobin

MetMb) which is grey-brown. The consumer associates the grey-brown color with undesirable products. Even small amounts of MetMb (<20%) have been found to reduce the sale of such discolored products (Renerre, M. 1990).

The relative amounts of Mb, MbO and MetMb in the meat depend on the oxygen availability, the autoxidation rate of Mb and the MetMb-reducing capacity. The oxygen availability depends on the oxygen partial pressure, the oxygen penetration and the oxygen consumption rate of the muscle (Ledward, 1992).

A layer of MbO is formed at the meat surface and, underneath a layer of MetMb is found. Further underneath, the myoglobin exists as Mb. The thickness of the MbO layer, and thus the distance from the surface to the MetMb layer, is dependent on the oxygen penetration. The depth to which oxygen diffuses in the meat depends on the oxygen consumption rate of the meat, the temperature and the external oxygen pressure. More MbO is formed at low temperatures and at low pH values, conditions that increase oxygen solubility and inhibit oxygen consumption.

The ratio of the different myoglobin forms observed at the meat surface is dependent on the thickness of the different myoglobin layers, as well as on the depth of light penetration during color measurements. The meat surface may be more or less translucent depending on the rate of post-mortem pH drop, ultimate pH, and the extent of protein denaturation. During post-mortem glycolysis, the sarcoplasmic proteins denature and precipitate on the myofibriles, resulting in increased light scattering and less light penetration. The internal reflectance of meat increases as pH decreases, even if no protein denaturation occurs, and this is probably related to decrease in myofilament spacing. The penetration depth of light decreases as an effect of increased light scattering due to an increased amount of water outside the myofibrillar space induced by the pH drop during glycolysis. At lower pH a thicker layer of MbO is formed and the formation of MetMb increases, while a higher pH a thinner layer of MbO and less MetMb is formed (Ledward, 1992).

Post-mortem glycolysis decreases muscle pH, making it brighter and superficially more wet. If the ultimate meat pH is high, the physical state of the proteins will be above their iso-electric point.

This meat is called DFD (dark, firm, and dry) and is dark because its surface does not scatter light to the same extent as meat with a lower final pH. The higher pH meat had a more open structure because the proteins repelled one another. Dark cutting beef results from cattle with lower than normal muscle glycogen stores at the time of slaughter which causes lower than normal lactic acid production after slaughter and a higher than normal ultimate meat pH.

Low muscle glycogen stores at slaughter preclude the development of a desirable pH after death. After a high pH and low temperature combination during rigor mortis, oxygen consumption by mitochondria at the surface of meat inhibits permeation of oxygen into the tissue and thereby inhibits conversion of myoglobin to oxymyoglobin. Low pH and higher temperature combination during rigor mortis inhibit mitochondrial activity so that more oxygen penetrates the meat surface and binds to the myoglobin molecule. Post-rigor oxygen consumption by mitochondria as affected by pH and temperature conditions, largely explains poor pigment oxygenation and poor color development in the extreme instance of dark cutting beef (Nichols and Cross, 1980).

Young et al. (1999) also found that as rigor develops, myofibrils become increasingly reflective at the warmer temperatures. The progressive increase in color values cannot be attributed to blooming because measurements were made immediately after cutting. The changes in color attributes might be due to a pH effect on deoxymyoglobin and other pigments in meat.

In addition to pH, the pigment state is influenced by oxygen and other components such as blooming time. To the eye, blooming is perceived as an increase in bright redness (Ledward, 1992). The a* and b* values increase during blooming, therefore blooming is probably well represented by chroma, $\sqrt{(a^{*2} + b^{*2})}$, and L*, the lightness. Young et al. (1999), in non-stimulated carcasses, reported that blooming was not fully complete at 12 h, occurring much more slowly than is commonly thought. They concluded that color measurements made would be sensitive to the exact time after exposure to air, which immediately questions the validity of color assessments made in chillers. A color measurement taken after allowing the meat to bloom for one hour could therefore give ambiguous results (Cassens et al., 1995).

DeVore (1974) considered that meat freshly in rigor could be actively consuming oxygen in the mitochondria, causing surface blooming to be reduced as oxygen is consumed.

Wulf and Wise (1999) evaluated the effect of bloom time on color measurements, collecting information of L*, a* and b* every 3 min thereafter up to 93 min after ribbing. The L* values obtained at all times following 30 min after ribbing did not differ ($P>0.05$) from the L* value obtained at 93 min after ribbing showing that it is less sensitive to bloom time. The a* and b* values continued to change until after 75 min of bloom time relative to the 93 min values. The coefficients of determination between colorimeter readings obtained at various times after ribbing and colorimeter readings obtained at 93 min after ribbing were greater than 0.9 for all times after ribbing beyond 3 min for all three colorimeter variables. In this study the carcasses were electric stimulated with low voltage.

It has been well established that muscle color is highly correlated with muscle pH (Wulf and Wise, 1999; Wulf and Page, 2000; Page et al., 2001). Muscle pH has been used as a more objective means of determining dark colored lean. Wulf et al. (1997) found a curvilinear relationship between L*, a* and b* values and pH and reported correlations of L*, a* and b* with muscle pH ($r= -0.57$, -0.79 and -0.78, respectively); however L* was a slightly poorer predictor of muscle pH than a* and b*. Page et al. (2001) reported that a* and b* values were more highly correlated with muscle pH ($r= -0.58$ and -0.56, respectively) than were values of L* ($r=-0.40$). For L* and b* values, it was observed that in a normal pH range (5.3 to 5.7) the colorimeter readings varied considerably whereas pH varied only slightly. In a pH range of 5.6 to 6.8, the colorimeter values varied only slightly whereas muscle pH varied considerably.

The negative correlations between colorimeter readings and muscle pH can be explained in that color in muscle tissues is based on the reflectance of light off free water and on oxygenation of the myoglobin (Ledward et al. 1992). At a higher muscle pH proteins are able to bind more strongly with water, allowing less free water. When the proteins bind more water, the muscle fibers are swollen, leaving less space between muscle fibers.

Meat that has a higher pH, therefore will be darker in color because there is less free water to reflect light (Ledward et al., 1992). Furthermore, at a higher muscle pH, enzymes that use oxygen are more active, resulting in less oxygenation of the surface myoglobin and a darker color

These studies of Wulf and Wise, 1999 and Page et al. 2001 indicate that muscle pH affects muscle color by altering hue rather than lightness/darkness, and that pH has greater affects on a* and b* than L* values. Meanwhile lean maturity is most highly associated with L* and is more a function of lightness/darkness.

With regard to predicting tenderness using colorimeter readings, Wulf et al. (1997) found a slightly stronger relationship between b* and tenderness than between L* and tenderness. The correlations reported by these authors between b* and WBSF and SPT were -0.38 and 0.37, respectively. For L*, the r were -0.36 and 0.34 for WBSF and SPT, respectively. Wulf and Page (2000) reported correlations in the range of -0.39 to -0.40 for colorimeter readings and WBS forces relationship.

Cannell et al. (1997) set out to augment the USDA grading system used the Hunter VIA technology to predict beef carcass palatability. They obtained a significant correlation ($P<0.05$) of -0.28 to -0.40 between L* and WBSF, but did not report a correlation between b* and shear force.

The reason for this relationship between final muscle pH, color and tenderness is not fully understood; however, a growing body of evidence suggests that these tenderness differences are related to differences in the rate and extent of post-mortem proteolysis. Wulf et al. (1997) indicated a relationship between muscle color (b*) and 24-h calpastatin activity (r=-0.28). Different studies showed that colorimeter readings (L*, a*, b*) explain approximately 20% of the *longissimus* shear force variation (Wulf et al., 1997; Wulf and Page, 2000).

The observation that color measurements were better predictors of tenderness compared with ultimate pH may be a result of at least two factors: a) the color measurements would probably be more repeatable than pH measurements, and b) they could be a better indicator of the rate of early-post-mortem pH decline.

Wulf and Page (2000) chose L* measurement among color and pH because of its ease of use and its expected repeatability. The effect of bloom time on L* is minimal compared with the effect of bloom time on b* (Wulf and Wise, 1999). However, if the problems of measuring pH can be overcome, final pH appears to be a useful tool for segregating carcasses according to their palatability.

Dark cutting beef (dark, firm and dry – DFD)

Meat quality issues, such as tenderness and dark cutting, currently burden the beef industry. A survey of purveyors, restaurateurs and retailers ranked both of these defects in the top ten primary concerns about the quality of meat (Smith et al., 1995). The 1995 National Beef Quality Audit reported that the incidence of dark cutting (DFD) beef carcasses in the United States is 2.7% and costs the beef industry $172 million annually (Smith et al., 1995). The Uruguayan beef industry is more concerned about this problem since the incidence of DFD is approximately 25%, according to preliminary results, and the real cost for the beef industry and Uruguayan exports is currently unknown.

Dark cutting beef is unattractive because of its dark red color and is discriminated against by the consumer when they can exercise a purchase choice, based on visual preference. The consumer discriminates against dark cutting beef in its fresh form and there is not clear evidence whether the palatability characteristics of dark cutters differ from normal beef. This is in agreement with results obtained by Viljoen et al. (2002). They found that more consumers preferred ($P<0.05$) normal pH steaks rather than DFD steaks because of the more attractive red color, again emphasizing the importance of an acceptable color for the consumer. Dumont (1981) stated that the importance of color as an indicator of freshness is probably overestimated in the consumer's mind.

Dark cutting beef results from cattle with lower than normal muscle glycogen stores at the time of slaughter which causes lower than normal lactic acid production after slaughter and a higher than normal ultimate pH. Further, meat with high ultimate pH is more susceptible to bacterial spoilage and has reduced flavor. Nevertheless, this meat is associated with a higher rate of tenderization (Watanabe et al., 1996; Beltrán et al., 1997) or with a better ultimate tenderness. Increases in tenderness associated with high pH have been shown in beef (Bouton et al., 1973; Dransfield, 1981;

Jeremiah, 1991; Lawrie, 1992; Dransfield, 1996; Silva et al., 1999). Dransfield (1981) found that DFD beef was on average more tender compared to normal pH meat.

Jeremiah et al. (1991) also reported that carcasses with the very darkest lean were tender; however, when those carcasses were excluded, a negative relationship existed between lean darkness and tenderness among steer and heifer carcasses. Lawrie (1992) mentioned that true DFD beef is characterized by extremely dark color, very high muscle pH and lower than normal shear force values. A possible explanation for the more tender DFD beef was related to the fragmentation of myofibrils being greater in DFD meat than normal meat and that the cooking losses are much smaller (higher water holding capacity).

Dransfield (1994) initially suggested that meat of high pH_u is more tender than normal pH meat as a result of a higher tenderization rate, but with prolonged aging the ultimate tenderness becomes similar. Silva et al. (1999) found that with the longer period of aging (13 days) the meat with higher pH_u was still more tender, demonstrating that the ultimate tenderness was influenced by pH_u.

Wulf et al. (1996) studied the effects of lean color on palatability and found a significant relationship with SPT scores. On the other hand, normal-colored lean received higher flavor intensity scores than dark-colored lean ($P<0.05$), which resulted in better acceptance of normal pH beef than DFD beef because consumers in general preferred the stronger beef flavor (Dransfield, 1981).

Page et al. (2001) found that a muscle pH value of approximately 5.87 was the approximate cutoff between normal and dark-cutting beef carcasses. Wulf et al.(2002) reported pH_u of 5.46 and 6.06 for normal and DFD carcasses, respectively. These authors, studied the effects of DFD status on beef palatability, and found that cooked beef palatability, measured by sensory panels, was substantially lower ($P<0.05$) for DFD carcasses than for normal carcasses (5.18 vs. 5.82, respectively). The *longissimus* from DFD carcasses had higher shear forces ($P<0.01$) than those from normal carcasses (5.47 vs. 3.72, respectively). Additionally, tenderness variation was greater (2.3 times) in DFD *longissimus* than in normal *longissimus*. Normal carcasses also produced more tender *longissimus* steaks than DFD carcasses (6.27 vs. 5.10, respectively) as rated by sensory panelists.

These conflicting results between previous studies and Wulf et al. (2002) could be explained by the curvilinear relationship between ultimate pH and meat tenderness with the maximum toughness at pH_u of 5.8 to 6.2. The carcasses that fall into the pH_u range associated with maximum toughness are DFD steer and heifer carcasses described in Dransfield et al. (1994).

Tenderness prediction systems among beef carcasses under commercial conditions

Because of the higher price of beef compared to other protein sources, the importance of a good eating experience is crucial to maintaining or improving current beef buying trends. The most influential palatability characteristic of the beef on eating satisfaction is tenderness. In the U.S., different studies were conducted to determine the tenderness of beef in the retail case and consumers' perception of taste. The National Beef Tenderness Surveys (Brooks et al., 2000) and the Beef Customer Satisfaction Study (Lorenzen et al., 2003) showed that tenderness could be a major and contributing factor to consumers' perception of taste. Moreover, other investigations have suggested that consumers have the ability to discriminate among tenderness categories and are willing to pay more for guaranteed tender beef products (Shackelford et al., 2001).

Boleman et al. (1997) established that it is possible that economic incentives may be used from retailers to packers to promote the production, identification and marketing of tender beef. Until some measure of the value of tenderness to the consumer is determined, there is limited research to convince those in the beef industry that tenderness is something to identify, manage, and market. Without information regarding economic incentives, the beef industry will continue to ignore tenderness and the variability in beef eating quality to the consumer will remain

The development of technologies that could be used by the beef packing industry to accurately characterize beef for tenderness has been a major focus of several researchers not only in the U.S., but also in Australia and New Zealand. The meat industry would prefer to be able to predict meat tenderness with a rapid, automated, non-invasive and accurate instrument. An accurate, instrumental method for classifying beef carcasses based on *longissimus* tenderness has been developed (Shackelford et al., 1999). Because the *longissimus* muscle comprises a higher proportion of total carcass value than any other muscle and, there is, more carcass-to-carcass tenderness variation

in *longissimus* than any other beef muscle (Shackelford et al., 1997), the need for tenderness classification is greatest for *longissimus*.

The Meat Animal Research Center (MARC) Beef Classification System is based on direct measure of tenderness through an objective measurement routinely used by meat scientist, the Warner-Bratzler shear force. Shackelford et al. (1999) determined that a high proportion (51%) of the variation in *longissimus* WBSF at 14 days after slaughter could be predicted by measuring shear force at 1 or 2 days post-mortem.

Since the inception of the USDA beef grading system in 1926, marbling score, defined as the amount and distribution of intramuscular fat in the longissimus muscle at 12-13th rib interface, has been used in the U.S. beef trade as the primary predictor of beef palatability among carcasses with similar maturity characteristics. To date, research has shown that marbling score has only a low to moderate relationship to beef palatability attributes. Smith et al. (1984) found substantial differences in steak palatability that are not related to marbling. Wulf et al. (1997) reported that USDA quality grade does not adequately differentiate *longissimus* tenderness of the 85% of fed-beef carcasses grading USDA Select or Low Choice. Previous studies had identified other carcass traits that might be used to replace or supplement marbling as a predictor of beef tenderness, such as subcutaneous fat thickness early-postmortem muscle pH and temperature, final pH and color.

Pike et al. (1993), Jones and Tatum (1994), and Shackelford et al. (1994) conducted studies to determine the effectiveness of singular and combined use of early-postmortem traits for predicting beef tenderness under commercial conditions. These studies reported that pH_3 accounted only for 0 to 16% of the WBSF variation and Shackelford et al. (1994) concluded that pH_3 was not an accurate indicator of tenderness for cattle slaughtered and processed under commercial conditions.

Other authors (Purchas, 1990, Watanabe et al., 1996 and Purchas et al., 1999) showed a relationship between ultimate pH and meat tenderness. Purchas (1990) and Purchas et al. (1999) found that pH_u explained 50 to 55% of the WBSF variation, in bull and steer carcasses. Watanabe et al. (1996), studying the response of the rate of aging per hour with pH_u reported a coefficient of determination (R^2) of 0.71 in a curvilinear relationship between variables.

Other indirect methods of predicting beef tenderness based primarily on lean color attributes and/or pH_u, have been developed with some promising results (Jeremiah et al., 1991, Cannell et al., 1997; Wulf et al., 1997; Wulf and Page, 2000). Wulf et al. (1997) evaluated whether objective measures of muscle color could be used to segregate beef carcasses into tenderness groups in 317 cattle of diverse breeds. They found that the colorimeter readings were superior to marbling score at segregating carcasses into tenderness groups and they explained by themselves 18% of the shear force variation. With the addition of pH to the color parameters in the model, these variables explained only 20% of the variation in tenderness. When the carcasses were segmented into three muscle color groups (lowest 25%, intermediate 50% and highest 25% based on colorimeter readings) the resulting groups had steaks that were 15, 3 and 0% tough, respectively, for SPT score of 4.5 (panel tenderness: 1= extremely tough; 8= extremely tender). According to these results, muscle color may be an effective critical control point in the process of ensuring tender beef.

Jeremiah et al. (1991) found that 13% of the variation in shear force values was accounted for colorimeter readings or final pH values in heifers and steers. In the case of bulls, pH_u and color accounted for 50% of its variation. These authors found a quadratic response between shear force values and colorimeter readings of muscle color and ultimate pH indicating that measurements of muscle pH and/or color may prove useful as a means for identifying tough carcasses. However, they suggested that segregation of beef carcasses by *longissimus* pH_u values between 5.8 and 6.2 appeared to be an easy, practical, nondestructive means to effectively differentiate tough carcasses. The segregation based on both muscle color and pH appeared to offer little advantage over the use of pH alone (Table 2.7).

Table 2.7 Percentages of carcasses within different sex groups segregated on the basis of muscle color and pH_u within specific ranges classified as tough (shear force >6.0)

Sex	Trait		
	Colorimeter[a] 8.5-16.49	pH_u 5.8-6.19	colorimeter/pH_u 8.5-16.49/5.8-6.19
Bulls	58.7	89.7	90.6
Heifers	53.6	77.2	79.5
Steers	48.9	63.8	67.7
Overall	51.9	71.7	75.0

[a](Reflectance readings: higher readings denoting lighter or paler color. Average readings for bulls:16.6, steers:17.7, heifers:17.0) Adapted from Jeremiah et al (1991)

Wulf and Page (2000), based on previous findings (Wulf et al., 1997), conducted another study to examine the effectiveness of using muscle color or pH among other variables to predict tenderness on randomly selected beef carcasses of unknown origin. Their results showed that muscle pH was useful to select carcasses with tender *longissimus* steaks (carcasses with muscle pH values ≤ 5.45 were more tender than carcasses with pH > 5.45) and color parameters in the *longissimus* were useful to segregate tough carcasses. Both variables (pH and color) explained 15 to 23% of the variation in beef palatability. They also proposed incorporating colorimeter measurements (in particular L* due to its expected repeatability and lowest sensitivity to bloom time) and hump height to the USDA quality grades to achieve a reduction in the beef palatability variation, mainly in the carcasses that grade U.S. Choice and Select.

Computer vision has shown a great potential for beef quality evaluation in that it is quickly implemented and noninvasive. Image processing techniques can quantitatively and consistently characterize complex color (Belk, 2000), measure crude fat content (Kuchida et al., 2000) and textural properties (Li et al., 1999). Colorado State University and Hunter Associates Laboratory scientists developed a video image analysis (VIA) system for measuring muscle and fat color in the ribeye of beef carcasses for sorting beef carcasses into expected tenderness groups. Belk et al. (2000) reported that a prototype video imaging system (BeefCam) could identify carcasses that produce tender steaks after aging and cooking. Recently, this prototype has been incorporated into the Computer Vision System (CVS). Vote et al. (2003) carried out research to determine the effectiveness of the CVS BeefCam for predicting WBS force values of *longissimus* steaks from beef carcasses and classifying

the carcasses according to tenderness differences. They found that the variables lean a* and lean b* were effective ($P<0.05$) in segregating carcasses into groups differing in tenderness measured by WBS forces. In agreement with the results presented by Wulf and Page (2000), the CVS BeefCam measurements accounted for greater amounts of variation in WBSF values than USDA quality grades when carcasses varied little in levels of marbling. The best model for predicting WBSF values in this study had a $R^2 = 0.30$. When the carcasses differed in marbling score, the USDA quality grades were more important in explaining this WBSF variation.

In a similar study, Wyle et al. (2003) tested the prototype BeefCam as a tool for sorting beef carcasses into expected palatability groups and reported a coefficient of determination (R^2) of 0.18 for a model (model I) using only prototype BeefCam measures as independent variables to predict WBS force values. When the USDA quality grade data was added to the prototype BeefCam, the model (model II) explained 21% of the WBSF variation. The first model did not lower ($P>0.05$) the percentage of carcasses that produced tough steaks in Top and Low Choice groups compared to no sorting, but lowered ($P<0.05$) the percentage of carcasses that produced tough steaks in the Select group compared with no sorting. The model II showed the same results (Table 2.8).

Table 2.8 Percentages of carcasses certified by model I and II and percentages of unacceptable carcasses based on WBSF values

		WBSF values that were tough (%)					
		Model I			Model II		
Quality group	n	Certified	Not Certified	Total	Certified	Not Certified	Total
Top Choice	241	4.3^{cy}	12.6^{cx}	7.9^{dxy}	4.8^{by}	18.9^{bcx}	7.9^{dy}
Low Choice	301	6.3^{cy}	16.0^{cx}	10.3^{cdy}	6.7^{by}	15.4^{cx}	10.3^{cdxy}
Select	227	16.5^{bz}	29.6^{bx}	24.7^{by}	4.4^{by}	29.7^{bx}	24.7^{bx}
All carcasses	769	7.8^{cz}	20.3^{cx}	13.8^{cy}	5.6^{bz}	23.2^{bcx}	13.8^{cy}

Tough: percentage of carcasses producing strip loin steaks with a WBSF value ≥ 4.5 kg
b,c,d Within a column, percentages that do not have a common superscript differ ($P<0.05$)
x,y,z Within a row and model, percentages that do not have a common superscript differ ($P<0.05$)
Adapted from Wyle et al. (2003)

The two studies (Vote et al., 2003 and Wyle et al., 2003) concluded that for these populations of beef carcasses sorting using the prototype BeefCam reduced the number of carcasses in the certified groups that generated steaks that were tough or unacceptable in overall palatability.

As direct comparisons of these methods (Wulf and Page, 2000; Belk et al., 2000 and Shackelford et al., 1999) have not been made, Wheeler et al. (2002) tried to determine the accuracy of these objective systems for identifying beef that could be guaranteed tender. They used carcasses graded as Choice (Top and Low) and Select. The three systems were evaluated based on progressive certification as tender in 10% increments. Regardless of percentage certified, the difference in mean *longissimus* WBSF value between certified and non-certified tender was significant ($P<0.05$) for both slice shear force and colorimeter for all carcasses. However, the magnitude of the differences in mean *longissimus* WBSF values between certified and non-certified tender was numerically greater for slice shear force than for colorimeter for all certification levels. This response ($P<0.05$) also was observed in the differences in mean *longissimus* trained sensory panels with the exception of the 90% certification level for colorimeter readings. In this trial, quality grade was relatively effective for identifying tenderness. Mean *longissimus* WBSF value was lowest ($P<0.05$) for Top Choice (3.55 kg) and highest ($P<0.05$) for Select (4.53 kg). Carcasses graded as Top or Low Choice (3.9 and 7.9%, respectively) had lower ($P<0.05$) percentages of steaks with WBSF values that were at least 5 kg than did Select carcasses (30.7%). These authors concluded that direct methods to predict meat tenderness, such as slice shear force, are necessary to obtain accurate identification of beef tenderness, since they are effective in both USDA Select carcasses and higher grading.

The method selected to identify guaranteed tender meat must be accurate enough to create a product that is recognizable by consumers as superior in tenderness. Some discrepancies exist among studies about the effectiveness of the systems. Although the direct method (slice shear force) seems to be more accurate, noninvasive technologies clearly show that objective measurements of muscle pH and/or color could be included in the USDA quality grading standards to improve the accuracy and precision of sorting beef carcasses into palatability groups. At the least muscle color and/or pH might ultimately be useful for inclusion of carcasses in a branded beef program that includes assurances of tenderness.

Literature Cited

Abril, M., M.M. Campo, A. Onenc, C. Sañudo, P. Albertí, and A.I. Negueruela. 2001. Beef color evolution as a function of ultimate pH. Meat Sci. 58:69-78.

AUS-MEAT. 1995. Handbook of Australian meat 5th ed. Australian Meat and Livestock Corporation, Brisbane, Queensland, Australia.

Bailey, A.J. 1972. The basis of meat texture. J. Sci. Food Agric. 23:995-1007.

Belk, K.E., J.A. Scanga, A.M. Wyle, D.M. Wulf, J.D. Tatum, J.O. Reagan, and G.C. Smith 2000. The use of video image analysis and instrumentation to predict beef palatability Proc. Recip. Meat Conf. 53:10-15.

Beltrán, J.A., I. Jaime, P. Santolaria, C. Sañudo, P. Albertí, and P. Roncalés. 1997. Effect of stress-induced high post-mortem pH on protease activity and tenderness beef. Meat Sci. 45(2):201-207.

Bendall, J.R. 1973. Post-mortem changes in muscle. In G.H. Bourne, *The structure and function of muscle* (pp 244- 306). New York: Academic Press.

Berry, B.W., G.C. Smith, and Z.L. Carpenter. 1974. Beef carcass maturity indicators and palatability attributes. J. Anim. Sci. 38:507-514.

Boakye, K. and G.S. Mittal. 1996. Changes in color of beef *M. longissimus dorsi* muscle during aging. Meat Sci. 42(3):347-354.

Boleman, S.J., S.L. Boleman, R.K. Miller, J.F. Taylor, H.R. Cross, T.L. Wheeler, M. Koohmaraie, S.D. Shackelford, M.F. Miller, R.L. West, and J.W. Savell. 1997. Consumer Evaluation of beef of known categories of tenderness. J. Anim. Sci. 75:1521-1524.

Bouton, P.E., P.V. Harris, and W.R. Shorthose. 1971. Effect of ultimate pH upon the water holding capacity and tenderness of mutton. J. Food Sci. 36:435-439.

Bouton, P.E., F.D. Carroll, P.V. Harris, and W.R. Shorthose. 1973. Influence of pH and fiber contraction state upon factors affecting the tenderness of bovine muscle. J. Food Sci. 38:404-407.

Bowling, R.A., G.C. Smith, T.R. Dutson, Z.L. Carpenter, and W.M. Oliver. 1977. Comparison of beef finished on forage versus grain. J. Anim. Sci. 45:209-215.

Brooks, J.C., J.B. Belew, D.B. Griffin, B.L. Gwartney, D.S. Hale, W.R. Henning, D.D. Johnson, J.B. Morgan, F.C Parrish, Jr., J.O. Reagan, and J.W. Savell. 2000. National Beef Tenderness Survey-1998. J. Anim. Sci. 78:1852-1860.

Cannell, R.C., K.E. Belk, C.D. Bunting, J.D. Tatum, and G.C. Smith. 1997. Ability of the Hunterlab color vision system to augment grading accuracy and to predict tenderness of beef. Proc. Recip. Meat Conf. 50:158.

Cassens, R.G., D. Demeyer, D. Eikelenboom, K.O. Honikel, G. Johansson, T. Nielsen, M. Renerre, I. Richardson, and R. Sakata. 1995. Recommendation of reference method for assessment of meat color. Proc. 41st ICoMST (pp. 410-411), San Antonio, TX, 20-25 August.

C.I.E., 1986. Colorimetry (2nd ed.) Commission International de l'Éclairage, Publication CIE 15.2. Vienna: CIE.

Davey, C.L., and K.V. Gilbert. 1973. The effect of carcass posture on cold, heat and thaw shortening in lamb. J. Food Technology. 8:445-451.

DeVore, D.P., and M. Goldberg. 1974. Oxygen uptake in post-rigor bovine muscle. J. Food Sci. 39:22-26.

Dikeman, M.E. 1996. The relationship of animal leanness to meat tenderness. Proc.Recip. Meat Conf. 49:87-101.

Dolezal, H.G., G.C. Smith, J.W. Savell, and Z.L. Carpenter. 1982. Comparison of sub-cutaneous fat thickness, marbling, and quality grade for predicting palatability of beef. J. Food Sci. 47:397-401.

Dransfield, E. 1981. Eating quality of DFD beef. In P.V. Tarrant and D.E. Hood (Eds), *The problem of dark-cutting in beef* (pp. 345-361). The Hague: Martinous Nijhoff.

Dransfield, E. 1993. Modelling post-mortem tenderisation-IV: Role of calpains and calpastatin in conditioning. Meat Sci. 34:217-234.

Dransfield, E. 1994. Tenderness of meat, poultry and fish. In A.M. Pearson and T.R. Dutson (Eds), *Quality attributes and their measurement in meat, poultry and fish products.* Advances in meat research series vol. 9 (pp. 289-315). London: Blackie Academic and Professional.

Dumont, B.L. 1981. Beef quality, marketing and the consumer. In D.E. Hood and P.V. Tarrant (Eds). *The problem of dark-cutting in beef* (pp. 37-57). The Hague: Martinous Nijhoff Publishers.

Ferrell, C.L. and T.G. Jenkins. 1996. Influence of body condition on productivity of cows. J. Anim. Sci. 74(Suppl.1):36.

Field, R.A.,M.L. Riley, F.C. Mello, M.H. Corbridge, and A.W. Kotula. 1974. Bone composition in cattle, pigs, sheep and poultry. J. Anim. Sci. 39:493-499.

Field, R., R. McCormick, V. Balasubramanian, D. Sanson, J. Wise, D. Hixon, M. Riley, and W. Russell. 1997. Tenderness variation among loin steaks from A and C maturity carcasses of heifers similar in chronological age. J. Anim. Sci. 75:693-699.

Guignot, F., C. Touraille, A. Ouali, and M. Renerre, 1994. Relationships between post-mortem pH changes and some traits of sensory quality in veal. Meat Sci. 37:315-325.

Hedrick, H.B., E.D. Aberle, J.C. Forrest, M.D. Judge, and R.A. Merkel. 1994. Principles of Meat Science. 3rd ed. Kendall/Hunt Publishing Company, Dubuque, IA.

Hilton, G.C., J.D. Tatum, S.E. Williams, K.E. Belk, F.L. Williams, J.W. Wise, and G.C. Smith. 1998. An evaluation of current and alternative systems for quality grading carcasses of mature slaughter cows. J. Anim. Sci. 76:2094-2104.

Huffhiness, C.P., G.C. Ledall, K.E McKissack, T.G. Field, M.A. Head, J.D. Tatum, J.W. Wise, and G.C. Smith. 1992. The effect of time-on-feed, electrical stimulation, marbling and subcutaneous fat thickness on the palatability of Hereford beef steaks. CSU Beef Program Report 1992: 167-173.

Hwang, I.H., and J.M. Thompson. 2001a. The effect of time and type of electrical stimulation on the calpain system and meat tenderness in beef *longissimus* muscle. Meat Sci. 58: 135-144.

Hwang, I.H., and J.M. Thompson. 2001b. The interaction between pH and temperature decline early post-mortem on the calpain system and objective tenderness in electrically stimulated beef *longissimus dorsi* muscle. Meat Sci. 58:167-174.

I.N.A.C. (1997). Sistema oficial (uruguayo) de clasificación y tipificación de carne vacuna. Resolución 65/97. Montevideo, Uruguay.

Jeremiah, L.E., A.K. Tong, and L.L. Gibson. 1991. The usefulness of muscle color and pH for segregating beef carcasses into tenderness groups. Meat Sci. 30: 97-114.

Jones, B.K. and J.D. Tatum. 1994. Predictors of beef tenderness among carcasses produced under commercial conditions. J. Anim. Sci. 72:1492-1501.

Kauffman, R.G. and B.B. Marsh. 1987. In *The science of meat and meat products*.3rd ed. J.F. Price and B.S. Scheigert. Food and Nutrition Press, Inc., Westport, CT, USA. pp.349-385.

Koohmaraie, M., S.C. Seideman, and J.D. Crouse. 1988. Effect of subcutaneous fat and high temperature conditioning on bovine meat tenderness. Meat Sci. 23:99-109.

Koohmaraie, M., S.C. Seideman, J.E. Schollmeyer, T.R. Dutson, and A.S. Babiker. 1988. Factors associated with the tenderness of three bovine muscles. J. Food Sci. 53(2): 407-410.

Koohmaraie, M. 1988. The role of endogenous proteases in meat tenderness. Proc. Recip. Meat Conf. 41:89-99.

Koohmaraie, M, G. Whipple, and J.D. Crouse. 1990. Acceleration of post-mortem tenderization in lamb and Brahman-cross beef carcasses through infusion of calcium chloride. J. Anim. Sci. 68:1278-1283.

Koohmaraie, M. 1996. Biochemical factors regulating the toughening and tenderization process of meat. Meat Sci. 43. S193-S201.

Kuchida, K., S. Kono, K. Konishi, L.D. Van Vleck, M. Suzuki, and S. Miyoshi. 2000. Prediction of crude fat content of *longissimus* muscle of beef using the ratio of fat area calculated from computer image analysis: Comparison of regression equations for prediction using different input devices at different stations. J. Anim. Sci. 78:799-803.

Laurent, K.M.,M.M. Pike, T.D. Bidner, A.M. Saxton, and A.M. McMillin. 1991. Effect of subcutaneous fat removal and aging on beef tenderness. J. Anim. Sci. 69(Suppl.2):19.

Lawrence, T.E., J.D. Whatley, T.H. Montgomery, and L.J. Perino. 2001a. A comparison of the USDA ossification-based maturity system to a system based on dentition. J. Anim. Sci. 79:1683-1690.

Lawrence, T.E., J.D. Whatley, T.H. Montgomery, L.J. Perino, and M.E. Dikeman. 2001b. Influence of dental carcass maturity classification on carcass traits and tenderness of *longissimus* steaks from commercially fed cattle. J. Anim. Sci. 79:2092-2096.

Lawrie, R. 1992. *The chemistry of muscle based foods*. Eds. E.Ledward, D. Johnston, and M. Knight. (pp 43-46). Royal Society of Chemistry, Cambridge, UK.

Ledward, D.A. 1992. Color of the raw and cooked meat. In D.E. Johnston, M. Knight, and D.A. Ledward. *The chemistry of muscle based foods*. Cambridge, UK:Royal Society of Chemistry .pp:128-144.

Lee, Y.B., and C.R. Ashmore. 1985. Effect of early post-mortem temperature on beef tenderness. J. Anim. Sci. 60:1588-1596.

Li, J., J. Tan, F.A. Martz, and H. Heymann. 1999. Image texture features as indicators of beef tenderness. Meat Sci. 53:17-22.

Light, N.D., A.E. Champion, C. Voyle, and A.J. Bailey. 1985. The role of epimysial, perimysial and endomysial collagen in determining texture in six bovine muscles. Meat Sci. 13:137-149.

Lochner, J.V., R.G. Kauffman, and B.B. Marsh. 1980. Early post-mortem cooling rate and beef tenderness. Meat Sci. 4:227-241.

Locker, R.H., and C.J. Hagyard. 1963. A cold shortening effect in beef muscles. J. Sci. Food and Agr. 14:787-793.

Lorenzen, C.L., R.K. Miller, J.F. Taylor, T.R. Neely, J.D. Tatum, J.W. Wise, M.J. Buyck, J.O. Reagan, and J.W. Savell. 2003. Beef Customer Satisfaction: Trained sensory panel ratings and Warner-Bratzler shear force values. J. Anim. Sci. 81:143-149.

Marsh, B.B. 1977. The basis of tenderness in muscle foods. J. Food Sci. 42:295-297.

Marsh, B.B., T.P. Ringkob, R.L. Russell, D.R. Swartz, and L.A. Pagel. 1987. Effects of early-postmortem glycolytic rate on beef tenderness. Meat Sci. 21:241-248.

May, S.G., H.G. Dolezal, D.R. Gill, F.K. Ray, and D.S. Buchanan. 1992. Effects of days fed, carcass grade traits and subcutaneous fat removal on post-mortem muscle characteristics and beef palatability. J. Anim. Sci. 70:444-453.

McCormick, R.J. 1999. Extracellular modifications to muscle collagen: implications for meat quality. Poultry Sci. 78:785-791.

Meyer, R.M., A.W. Young, B.B. Marsh, and R.G. Kauffman. 1977. Effect of backfat in preventing cold shortening and maintaining tenderness in beef. J. Anim. Sci.(Suppl.1) 45:70 (Abstr.).

Nichols, J.E., and H.R. Cross. 1980. Effects of electrical stimulation and early post-mortem muscle excision on pH decline, sarcomere length and color in beef muscles. J. Food Protection. 43(7):514-519.

NLSMB. 1995. Beef Customer Satisfaction. National Livestock and Meat Board, Chicago, Il.

O'Halloran, G.R., D.J. Troy, and D.J. Buckley. 1997. The relationship between early post-mortem pH and the tenderisation of beef muscles. Meat Sci. 45(2):239-251.

Owens, F.N. and B.A. Gardner. 1999. Ruminant nutrition and meat quality. Proc. Recip. Meat Conf. 52:25-36.

Page, J.K., D.M. Wulf, and T.R. Schwotzer. 2001. A survey of beef muscle color and pH. J. Anim. Sci. 79:678-687.

Pearson, A.M., and R.B. Young. 1989. In *Muscle and meat biochemistry* (pp 160-185) San Diego: AcademicPress.

Pike, M.M., T.P. Ringkob, D.D. Beekman, Y.O. Koh, and W.T. Gerthoffer. 1993. Quadratic relationship between early post-mortem glycolytic rate and beef tenderness. Meat Sci. 34:13-26.

Purchas, R.W. 1990. An assessment of the role of pH differences in determining the relative tenderness of meat from bulls and steers. Meat Sci. 27:129-140.

Purchas, R.W., and R. Aungsupakorn. 1993. Further investigations into the relationship between ultimate pH and tenderness of beef samples from bulls and steers. Meat Sci. 34:163-178.

Purchas, R. W., X. Yan, and D.G. Hartley. 1999. The influence of a period of aging on the relationship between ultimate pH and shear values of beef *m. longissimus thoracis.* Meat Sci. 51:135-141.

Renerre, M. 1990. Review: Factors involved in the discoloration of beef meat. Int. J. Food Sci. and Tech. 25:613-630.

Shackelford, S.D, M. Koohmaraie, G. Whipple, T.L. Wheeler, M.F. Miller, J.D. Crouse, and J.O. Reagan. 1991. Predictors of beef tenderness: Development and verification. J. Food Sci. 56(5):1130-1135.

Shackelford, S.D., M. Koohmaraie, and T.L. Wheeler. 1994a. The efficacy of adding a minimum adjusted fat thickness requirement to the USDA beef quality grading standards for select grade beef. J. Anim. Sci. 72:1502-1507.

Shackelford, S.D., M. Koohmaraie, L.V. Cundiff; K.E. Gregory, G.A. Rohrer, and J.W. Savell. 1994b. Heritabilities and phenotypic and genetic correlations for bovine postrigor calpastatin activity, intramuscular fat content, Warner-Bratzler shear force, retail product yield and growth rate. J. Anim. Sci. 72:857-863.

Shackelford, S.D., M. Koohmaraie, and J.W. Savell. 1994c. Evaluation of *longissimus dorsi* muscle pH at three hours post-mortem as a predictor of beef tenderness. Meat Sci. 37: 195-204.

Shackelford, S.D., T.L. Wheeler, and M. Koohmaraie. 1997. Repeatability of tenderness measurements in beef round muscles. J. Anim. Sci. 75:2411-2416.

Shackelford, S.D, T.L. Wheeler, and M. Koohmaraie. 1999. Tenderness classification of beef II. Design and analysis of a system to measure beef *longissimus* shear force under commercial processing conditions. J. Anim. Sci. 77:1474-1481.

Shackelford, S.D, T.L. Wheeler, M.K. Meade, J.O. Reagan, B.L. Byrnes, and M.Koohmaraie. 2001. Consumer impressions of Tender Select beef. J. Anim. Sci. 79:2605-2614.

Silva, J.A., L. Patarata, and C. Martins. 1999. Influence of ultimate pH on bovine meat tenderness during aging. Meat Sci. 52:453-459.

Simmons, N.J., M.M. Auld, B. Thomson, J.M. Cairney and C.C. Daly. 2000. Relationship between intermediate pH toughness in the striploin and other muscles of the beef carcass. Proceedings of the New Zealand Society of Animal Production. 60:117-119.

Smith, G.C., Z.L. Carpenter, H.R. Cross, C.E. Murphey, H.C. Abrahan, J.W. Savell, G.W. Davis, B.W. Berry, and F.C. Parrish Jr. 1984. Relationship of USDA marbling groups to palatability of cooked beef. J. Food Qual. 7:289-308.

Smith, G.C., H.G. Dolezal, and J.W. Savell. 1995. The final report of the National Beef Quality Audit-1995. Colorado State Univ., Fort Collins; Oklahoma State Univ., Stillwater, and Texas A&M Univ., College Station.

Smulders, F.J.M., B.B.Marsh, D.R. Swartz, R.L. Russell, and E. Hoenecke. 1990. Beef tenderness and sarcomere length. Meat Sci. 28:349-363.

Takahashi, K. (1996). Structural weakening of skeletal muscle tissue during post-mortem aging of meat: the non-enzymatic mechanism of meat tenderization. Meat Sci. 43:S67-S80.

Tarrant, K. 1981. The occurrence, causes and economic consequences of dark-cutting in beef- a survey of current information. In P.V. Tarrant and D.E. Hood. *The problem of dark-cutting in beef* (pp. 199-212) The Hague: Martinous Nijhoff.

Tatum, J.D., G.C. Smith, and Z.L. Carpenter. 1982. Interrelationships between marbling, subcutaneous fat thickness and cooked beef palatability. J. Anim. Sci. 54:777-784.

Tatum, J.D., K.E. Belk, M.H. George, and G.C. Smith. 1999. Identification of quality management practices to reduce the incidence of retail beef tenderness problems: Development a prototype quality system to produce tender beef. J. Anim. Sci. 77:2112-2118.

Thompson, J. 2002. Managing meat tenderness. Meat Sci. 62:295-308.

USDA. 1997. Official United States standards for grades of carcass beef. Agric. Marketing Serv., USDA, Washington, DC.

Viljoen, H.F., H.L. de Kock, and E.C. Webb. 2002. Consumer acceptability of dark, firm and Dry (DFD) and normal pH beef steaks. Meat Sci. 61:181-185.

Vote, D.J., K.E. Belk, J.D. Tatum, J.A. Scanga, and G.C. Smith. 2003. Online prediction of beef tenderness using a computer vision system equipped with a BeefCam module. J. Anim. Sci. 81:457-465.

Watanabe, A., C.C. Daly, and C.E. Devine. 1996. The effects of the ultimate pH of meat on tenderness changes during aging. Meat Sci. 42(1):67-78.

Wheeler, T.L., L.V. Cundiff, and R.M. Koch. 1994. Effect of marbling degree on beef palatability in *Bos taurus* and *Bos indicus* cattle. J. Anim. Sci. 72:3145-3151.

Wheeler, T.L., S.D. Shackelford, and M. Koohmaraie. 1999. MARC Beef classification system. Proc. Recip. Meat Conf. 52:53-55.

Wheeler, T.L., S.D. Shackelford, and M. Koohmaraie. 2000. Relationship of beef *longissimus* tenderness classes to tenderness of *gluteus medius*, *semimembranosus*, and *biceps femoris*. J. Anim. Sci. 78:2856-2861.

Wheeler, T.L., D. Vote, J.M. Leheska, S.D. Shackelford, K.E. Belk, D.M. Wulf, B.L. Gwartney, and M. Koohmaraie. 2002. The efficacy of three systems for identifying beef cuts that can be guaranteed tender. J. Anim. Sci. 80:3315-3327.

Wulf, D.M., J.B. Morgan, J.D. Tatum, and G.C. Smith. 1996. Effects of animal age, marbling score, calpastatin activity, subprimal cut, calcium injection, and degree of doneness on the palatability of steaks from Limousin steers. J. Anim. Sci. 74: 569-576.

Wulf, D.M., S.F. O'Connor, J. D. Tatum, and G. C. Smith. 1997. Using objective measures of muscle color to predict beef *longissimus* tenderness. J. Anim. Sci. 75:684-692.

Wulf, D.M. and J.W. Wise. 1999. Measuring muscle color on beef carcasses using the L* a* b* color space. J. Anim. Sci. 77:2418-2427.

Wulf, D.M. and J.K. Page. 2000. Using measurements of muscle color, pH, and electrical impedance to augment the current USDA beef quality grading standards and improve the accuracy and precision of sorting carcasses into palatability groups. J. Anim. Sci. 78:2595-2607.

Wulf, D.M., R.S. Emnett, J.M. Leheska, and S.J. Moeller. 2002. Relationships among glycolytic potential, dark cutting (dark, firm, and dry) beef, and cooked beef palatability. J. Anim. Sci. 80:1895-1903.

Wyle, A.M., D.J. Vote, D.L. Roeber, R.C. Cannell, K.E. Belk, J.A. Scanga, M. Goldberg, J.D. Tatum, and G.C. Smith. 2003. Effectiveness of the SmartMV prototype BeefCam system to sort beef carcasses into expected palatability groups. J. Anim. Sci. 81:441-448.

Wythes, J.R., and W.R. Shorthose. 1991. Chronological age and dentition effects on carcass and meat quality of cattle in northern Australia. Aust. J. Exp. Agric. 31:145-152.

Young, O.A., A. Pirolo, N.J. Simmons, and J. West. 1999. Effects of rigor attainment temperature on meat blooming and color on display. Meat Sci. 52:47-56.

Yu, L.P. and Y.B. Lee. (1986). Effects of post-mortem pH and temperature on bovine muscle structure and meat tenderness. J. Food Sci. 51:774-780

CHAPTER 3

PREDICTING AND SEGREGATING BEEF TENDERNESS AMONG URUGUAYAN FEMALE CARCASSES UNDER COMMERCIAL CONDITIONS USING POSTMORTEM CARCASS TRAITS, pH, TEMPERATURE AND COLORIMETER READINGS [1]

[1] Brito, G., D. Pringle and D. J. Vote To be submitted to Journal of Animal Science

Abstract

This research was conducted to determine whether objective measures of muscle pH, temperature and color are useful to segregate Uruguayan female beef carcasses by tenderness and to determine whether USDA quality grading standards (QG) for beef carcasses could be applied to Uruguayan female beef carcasses to improve the effectiveness of this segregation. Female beef carcasses (n=163) were selected at one packing plant to represent the commercial conditions of Uruguayan cattle. Temperature (T_1, T_3 and T_u), pH (pH_1, pH_3 and pH_u) and colorimeter readings (L*, a* and b*) at ribbing were collected postmortem. Longissimus muscle samples were removed from each carcass and Warner Bratzler shear forces were measured after 7 (WBSF7) and 14 days of aging (WBSF14). Tenderness differences were explained mainly by dentition. Carcasses with $pH_3 < 5.8$, and a* values ≥ 20 showed the lowest WBSF. WBSF14 was highly correlated (r) to USDA lean maturity and color values ($P<0.01$). The r between a* and pH_u was -0.47 ($P <0.01$). The relationship between pH_u and 1/WBSF7 ($R^2=0.13$) and between colorimeter readings (1/a* $R^2=0.20$; 1/b* $R^2=0.14$) and WBSF7 were quadratic. Carcasses with a* values ≥ 20 had lower WBSF7 and WBSF14 (3.97 and 3.42 kg, respectively, $P<0.01$) than carcasses with a* < 20 (5.36 and 4.51 kg, respectively). Within QG, lean and overall maturity explained 15 and 23% of the variation in WBSF7 and WBSF14, respectively, whereas a* value accounted for 32 and 33% of WBSF7 and WBSF14 variation among steaks for all carcasses. A multiple linear regression equation developed with QG, linear and quadratic a* and pH_u to predict WBSF7 and WBSF14 showed adjusted $R^2=0.34$ and 0.38, respectively. An accuracy of 75.6% and 79.5% for WBSF7 and WBSF14 was observed in predicting whether a steak would be classified as tender using a WBSF threshold of 4.5 kg. QG, pH_u and color (a*) measured at ribbing in Uruguayan commercial conditions would allow prediction of steak tenderness and segregation of female beef carcasses into tenderness groups, thus improving the consistency of this characteristic.

Key Words: Beef, Female, Color, pH, Temperature, Tenderness

1. Introduction

The loss of market share in the beef industry has led to strategies to create value in beef at all levels of marketing and production in order to meet consumer expectations. The beef industry is evolving from selling a commodity to marketing a product, and branded beef programs are emerging rapidly. As outlined by many authors, quality improvements must be driven by consumer expectations and perceptions since they are the ultimate users and since food quality is so closely related with acceptability (Issanchou, 1996).

As beef is merchandized at retail, consumers evaluate several factors when buying a cut. The visual appraisal of meat products can determine whether a consumer will make a purchase (Hedrick et al., 1994). Measurements of lean color have been related to carcass maturity (USDA, 1997) and muscle pH (Jeremiah et al., 1991; Wulf and Page, 2000; Page et al., 2001; Wulf et al., 2002). Muscle color is also important because researchers have shown its relationship with meat tenderness (Jeremiah et al., 1991, Wulf et al., 1997; Wulf and Page, 2001, Wulf et al., 2002; Vote et al., 2003). It also has been demonstrated that ultimate pH is correlated with tenderness (Purchas, 1990, Silva, 1999, Wulf et al., 2002). To meet consumer expectations, beef industries in different countries (United States, New Zealand and Australia) have identified the problem of inconsistent meat tenderness as a priority. There is a growing interest on the part of beef industries to develop a carcass classification system that would more accurately predict beef palatability, particularly tenderness and to implement different meat quality programs (ex: Tenderness Guarantee, Meat Standard of Australia and New Zealand Beef and Lamb Quality Marks). Uruguay, as a fresh meat export country, should be allied to this strategy that is developing in the main beef producing and export countries. However, a significant effort must be made to convince those in the Uruguayan beef industry that tenderness is something to identify, to manage and to market. Without information regarding economic incentives, most entities within the beef industry will continue to ignore tenderness and beef will remain variable in its eating quality.

This study was conducted to determine whether objective measures of muscle color, muscle pH and temperature are useful to predict tenderness on randomly selected female beef carcasses of unknown origin, and to determine whether the application of USDA quality grading standards to Uruguayan beef carcasses could improve their segregation into tenderness categories.

2. Materials and Methods

A group of 163 female beef carcasses of unknown origin was selected at one packing plant in Uruguay, in May 2002. Carcasses were selected at the time of grading in Uruguay and they were not electrically stimulated. Carcasses were chosen based on two age classes by dentition (0- 4 teeth, n=43 and 8 teeth, n=110) and two fat thickness classes (≤ 7mm, n=72 and >7 mm, n=81). The reason to distinguish these two age classes was based on use in export versus domestic markets (0-4 teeth: Chile and Mercosur; 8 teeth: domestic), No differences in yield and quality traits among 0, 2 and 4 teeth carcasses were evaluated in this experiment. The hot carcass weight (HCW) was recorded and the 8 teeth group was segregated into two classes (<215kg, n=100 and ≥ 215 kg, n=53) for the 8 teeth group. The number of carcasses in the 0-4 teeth and > 215 kg was very small (n=10) and thus this group was eliminated from the analysis. Carcasses were segregated into appropriate fat thickness categories based on actual carcass backfat measured at the 11^{th} rib surface. Two official classification systems were applied, the American (USDA, 1997) and the Uruguayan (INAC, 1997) at different times. The Uruguayan system was applied on hot carcasses (1 h postmortem), while the USDA system was applied on cold carcasses 18-24 h postmortem, approximately. Colorado State University personnel collected data for preliminary yield grade, percentage kidney, pelvic, and heart fat, lean maturity, skeletal maturity, overall maturity, marbling score and quality grade. The following carcass data were collected at ribbing on the left side of the carcass at the 11^{th} rib cut surface of the *longissimus dorsi*: actual backfat, ribeye area (output from a cold computer vision system, CVS, Research Management Systems, USA), lean colorimeter measures (L*, a*, b*), and muscle pH and temperature. The lean colorimeter readings were collected one hour later after adequate bloom time.

An 8-cm portion of the *longissimus dorsi* was removed from the left side of carcasses, labeled, vacuum-packaged and transported to the Meat Science Laboratory at INIA Tacuarembó for shear force analysis after 7 and 14 days of aging at 2 - 4 ^{o}C.

2.1. pH Measurements

The pH of the *longissimus dorsi* was determined at three different times: 1, 3 and 18-24 h postmortem. The pH 1 and 3 h postmortem was measured between the 10 and 11th rib on the left side of the carcasses, at a depth of 2 cm. The ultimate pH measurement (18-24 h postmortem) was taken at the 11th rib cut surface in the pistola cut. The muscle pH was measured using a hand-held pH meter (Orion A 230) with a probe type electrode (BC 200, Hanna Instruments), standardized against two pH buffers (4 and 7). The probe was cleaned with alcohol and rinsed with water between uses.

2.2. Temperature Determination

The temperature was determined at 1, 3, and 18-24 h postmortem. In the first two measurements, the temperature was taken between the 10 and 11th rib on the left side of the carcasses. The ultimate temperature (18-24 h postmortem) was collected at the 11th rib cut surface in the pistola cut. In each case, the temperature was determined by a thermometer (Barnant 115) with stainless steel thermocouple (type E).

2.3. Muscle Color Determination

Muscle color measurements followed the CIE color convention (CIE, 1986), where the three fundamental outputs are L*, a* and b*. L* is lightness on a scale of 0 (all light absorbed) to 100 (all light reflected); a* spans from + 60 (red) to – 60 (green) and b* spans from + 60 (yellow) to – 60 (blue). Color measurements were made using a Minolta Colorimeter (model C-10) with a 50mm diameter measurement area. They were recorded in triplicate from the exposed *longissimus* muscle between the 10-11th rib immediately following ribbing (cutting between the 10-11th to expose the *longissimus* muscle) surface in the pistola cut (left side). After 1 h post-ribbing and to examine the effect of blooming on the three outputs (L*, a*, b*), the colorimeter readings were collected following the same procedure (L*b, a*b, b*b).

2.4. Warner-Bratzler Shear Force Determination

The portions of *longissimus dorsi* transported to the Meat Science Laboratory at INIA Tacuarembó were aged for 7 and 14 days at 2-4 ^{o}C. At 7d postmortem, the cuts were trimmed and sliced to generate 2.54 cm thick steaks. The first steak (at the anterior end) from each *longissimus* was used for shear force determination with 7 d of aging, the second was vacuum-packaged and aged another 7 days for subsequent Warner-Bratzler shear force analysis (WBSF), and the rest of the cut was frozen (-20^{o}C) for further analysis. The steaks aged 7 and 14 days were cooked by immersion within a plastic bag in a water bath (80 ^{o}C) at an internal temperature of 70^{o}C for 90 min. The internal temperature was monitored using type E thermocouples placed in the approximate geometric center of the steak. Six cores (1.27 cm in diameter), parallel to the muscle fiber orientation, were removed from each steak. A single peak WBSF measurement was obtained for each core using a WBSF machine (G-R Electric Manufacturing Co, Manhattan, KS). Individual-core peak shear force values were averaged to assign a mean peak WBSF value to each steak.

2.5. Statistical analysis

Descriptive statistics were computed in this experiment for selected carcass traits, pH, temperature, colorimeter readings and WBSF values. A Shapiro-Wilk test ($P<0.01$) from Univariate procedure (SAS, 1990) was conducted to determine whether these variables had a normal distribution. An inverse transformation was used for the variables t1, b* and bb* (blooming), and a cubic exponential one was used for L* and Lb* (blooming) to obtain a normal distribution for these variables.

The model used in this experiment was

$$Y_{ijkl} = \mu + A_i + B_j + C_k + ABC_{ijk} + E_{ijkl}$$

where

Y_{ijkl} = ijklth Warner-Bratzler shear force at 7 and 14 days of aging,

μ = overall mean,

A_i = effect of the ith dentition,

B_j = effect of the j^{th} hot carcass weight,

C_k= effect of the k^{th} fat thickness

ABC_{ijk}= interaction effect of ijk^{th} dentition * hot carcass weight*fat thickness,

E_{ijkl} = residual error

The interaction effect among variables was not significant ($P<0.05$), and was not considered in further statistical analysis. Least squares means were separated using the PDIFF procedure.

To better understand the relationship between the independent and the dependent (WBSF values) variables the data was analyzed by correlation and regression techniques The multiple regression equations were computed by stepwise procedures (SAS, 1990). Objective muscle color measurements and muscle pH values were plotted against mean shear force values, and coefficients of determination (R^2) between these variables were obtained with the mentioned procedures. Contingency tables were analyzed to determine the efficacy of sorting carcasses by tenderness class using the selected model.

3. Results and Discussion

3.1. Carcass Characteristics.

The definition of each variable is presented in Table 3.1. Means and standard deviation for hot carcasses weight, rib eye area, fat thickness, conformation and finishing by INAC system, preliminary yield grade, skeletal maturity, lean maturity, marbling score, and quality grade by USDA system, pH and temperature at 1, 3 and ultimate, L*, a*, and b* values without and with blooming and WBSF for 7 and 14 days of aging are presented in Table 3.2 for all female carcasses.

The average for WBSF 7 and WBSF 14 were 4.67 kg (CV= 36.5) and 3.96 kg (CV= 33.7) The frequency of these carcasses in each USDA quality categories (overall maturity, marbling and quality grade) is presented in Table 3.3, for a better understanding of the composition of these populations. The statistical analysis for the mentioned model showed that only dentition was significant ($P<0.01$) for WBSF at 7 and 14 days. No differences were found ($P>0.05$) in quality and yield traits among carcasses with 0 to 4 teeth (data not shown). With this information, the descriptive

statistics for each dentition group (0-4 teeth=YO and 8 teeth=OL) are presented in Table 3.2. The groups (Table 3.4) were different (P<0.01) in HCW (YO= 179.1 kg vs. OL=214.1 kg) but were similar (P>0.05) in fat thickness (FAT) (YO=8.6 mm vs. OL=8.5 mm), and yield grade (YO=2.99 vs. OL=2.95). These groups also differed (P<0.01) in ribeye area adjusted by 50 kg of carcass weight (YO=12.76 vs. OL=11.14) (data not shown).

In the YO group, 85% of carcasses were classified as A in overall maturity. In marbling score (MARB) 60.38% of the carcasses had Slight marbling, while 32.1% was classified as having Traces levels of marbling. Assigning the USDA quality grade, 51% of these carcasses were classified as Select, while 41.5% of them were Standard. The older (OL) female carcasses were classified as C (41%) and D (31.8%) in overall maturity. For MARB, 56.4% were graded as Slight and 29% were found with Traces levels of intramuscular fat. The predominant quality grade for this OL carcass group was Utility (68.2%) followed by the Cutter category (12%).

Relating the effect of FAT and QG to tenderness, the carcasses graded as Select had FAT ≥ 7 mm, while the Standard carcasses were divided in 3 classes of FAT (<5mm, 5-7mm, and ≥ 7mm) to study whether there was any effect of this variable on WBSF. There was no difference (P>0.05) in WBSF7 or WBSF14 among FAT classes within Standard carcasses (data not shown). Likewise, no difference (P>0.05) in tenderness was found in Utility grade carcasses for the 3 FAT levels. Jones and Tatum (1994) found that Select carcasses with ≥ 5 mm fat thickness had lower WBSF (2.70 kg) than Select carcasses with < 5 mm of fat thickness (3.05 kg, P<0.05). However, Shackelford et al (1994) concluded that the addition of ≥ 5mm fat thickness for the Select grade would not improve tenderness significantly although it should reduce tenderness variation in Select grade carcasses.

The OL carcasses had higher temperatures at 1 (T_1) and 3 (T_3) h postmortem (P<0.01 and P<0.05, respectively) than the YO carcasses, mainly due to differences in HCW since both groups were similar in fat thickness. Similar differences were not found in the pH values, with the pH values at 1 (pH_1) and 3 (pH_3) h postmortem lower (P<0.01) for YO group than for OL one. There were no significant differences (P>0.05) for pH and temperature at 24 h postmortem (pH_u and T_u). The colorimeter readings L* and b* were significantly different (P<0.01), while a* was different at 5%

between groups. These differences between groups were expected due to age differences, since the myoglobin concentration should increase with age causing a darker color (Hedrick et al., 1994)

The WBSF values for 7 and 14 days of aging (WBSF7 and WBSF14, respectively) were different ($P<0.01$) between groups, although this level was lower compared with the results reported by Shackelford et al. (1991) where WBSF values > 4.5 kg are considered tough. These differences between groups are explained essentially by the differences in age and overall maturity ($P<0.01$), since no differences ($P>0.05$) were found in marbling scores (Table 3.4).

The former comparison was done considering only the effect of the age. In Table 3.5, the comparison of FAT (≤7 and >7 mm) and age groups (YO and OL) is shown for HCW < 215 kg. The MARB score increases with the levels of fat. The differences were significant ($P<0.01$) for MARB within YO, however within OL, no significant differences ($P>0.05$) were found between age groups although the fatter class (>7 mm) showed more MARB than the leaner class. There was no difference in MARB between treatments, which differ only in dentition. The differences in the other variables of quality grade were explained previously.

In analyzing the pH values, there were differences ($P<0.05$) between treatments within YO for pH_1 and pH_3, showing the fatter carcasses had lower pH than the leaner ones. Bowling et al (1977) explained that the insulation effect of moderate levels of subcutaneous fat reduce the rate of carcass temperature decline and accelerate the glycolysis rate during post-mortem chilling. This result is in agreement with Laurent et al. (1991) who found that carcass sides with fat removed had lower temperatures and higher pH at 1 h post-mortem. In OL carcasses no differences were found in pH_1 and pH_3 ($P>0.05$), however, pH_u was different ($P<0.05$). The fattest carcasses group showed the lowest pH_u, independent of age. The temperatures for all treatments were similar ($P>0.05$).

Colorimeter readings also increased with level of FAT in the YO group. L* and b* were significantly different ($P<0.05$) within this group, but there was no difference ($P>0.05$) in the OL group. The same conclusion is made for the color values after blooming. Page et al. (2001) reported a backfat threshold (7.6 mm) for lean color values, with carcasses containing less than 7.6 mm of backfat having darker meat and higher muscle pH than carcasses with backfat > 7.6 mm.

Differences in WBSF values were primarily explained by age. Within age group there was some evidence (P>0.05) of the effect of FAT on the final tenderness measurement for both aging periods (greater levels of fat trend to decrease WBSF)**.** Tatum et al. (1982) found that leaner carcasses produced less tender steaks. In agreement, Page et al. (2001) reported that carcass with backfat levels below 7.6 mm produced less tender beef. The differences in tenderness were explained in part to the insulation effect of the fat slowing down the carcass chilling process and affecting the glycolytic metabolism.

The OL group had more variation in carcass composition than the YO group. This allowed us to study the combination of HCW (<215 and ≥ 215 kg) and FAT (≤ 7 and > 7 mm) (Table 3.6). Lean maturity was lower for the carcasses with FAT > 7 mm and HCW ≥ 215 kg, (P<0.05) compared to carcasses with ≤ 7 mm FAT. A similar trend was noted in MARB. In addition, pH_1, pH_3, T_1 and T_3 were higher for HCW ≥ 215 kg and FAT > 7 mm than other groups (Table 3.6).

The WBSF values for 7 and 14 days were not different (P>0.05) between groups, but the fattest carcasses showed a trend to have lower WBSF values in both aging periods than the leanest carcasses. Considering the aforementioned threshold (tough ≥ 4.5 kg), the treatment HCW ≥ 215 kg and FAT ≤ 7 mm had higher WBSF14 higher (4.67 kg) than 4.5 kg. With 7 days of aging all WBSF values were higher than the WBSF threshold. This confirms that the differences in WBSF in this study were explained basically by age.

3.2. Correlation analyses

Simple correlations of carcass traits and WBSF are presented in Table 3.7. For the yields component, FAT had the highest correlation (r=0.8) with YG. Quality grade and skeletal maturity were most closely (P<0.01) related with dentition (r= -0.74 and 0.78, respectively). This relation was expected because in this study 0-4 teeth were compared with 8-teeth carcasses. Lawrence et al. (2001) showed little evidence of agreement between age estimates derived from the USDA ossification maturity system and the number of permanent incisors present at slaughter. This was confirmed in this study for carcasses presenting 0 to 4 teeth, where 85% of them were graded A.

Marbling was negatively correlated ($P<0.05$) with WBSF7 ($r = -0.17$) and WBSF14 ($r = -0.19$). Vote et al. (2003) for CVS BeefCam marbling reported correlations in the order of -0.04 to -0.34 for different experiments, while Wulf et al. (1997) found a $r= -0.12$ for the relationship between marbling score and shear force.

In this analysis we used the color measurements taken at ribbing, without blooming, because blooming did not contribute to improving the correlation coefficients. Lean maturity showed a high negative correlation with L* ($r=-0.72$, $P<0.01$). Vote et al. (2003) reported correlations between lean maturity and CVS BeefCam lean L* in the range -0.52 to -0.69. Previously, Page et al. (2001) had found a $r= -0.58$ between these variables. Lean maturity was also correlated ($P<0.01$) with a* ($r= -0.56$) and b* ($r = -0.65$) in this study. Vote et al (2002) and Page et al. (2001) reported lower r between lean maturity and a* ($r= - 0.27$ to -0.34), and b* ($r=-0.15$ to -0.43) than our study. When this variable, lean maturity, was related with WBSF7 and WBSF14, the r value was 0.38 and 0.47, respectively ($P<0.01$). Vote et al. (2003) reported r from 0.04 to 0.34 between lean maturity and WBSF14.

The simple correlations between pH_u and colorimeter readings were moderate to high in this study. The r for pH_u and L*, a*, and b* were -0.38, -0.47, and -0.46, respectively ($P<0.01$). The negative correlations between colorimeter readings and pH_u could be explained in that color in muscle tissue is based on reflectance of light off free water and on oxygenation of the myoglobin (Ledward et al., 1992). Wulf et al. (1997) and Page et al. (2001) reported similar correlation coefficients among these variables of -0.48 and -0.40 for pH_u and L*, -0.52 and -0.58 for a* and pH_u, and –0.60 and –0.56 for b* and pH_u, respectively.

All correlation coefficients between lean color and WBSF were negative. This could be explained because few carcasses with dark lean were found to be tender in this population. This could be due to age differences in the carcasses since older carcasses would be darker and tougher than younger carcasses. These results are in agreement with other findings (Cannell et al., 1997; Wulf et al., 1997; Wulf and Page, 2000; and Vote et al., 2003). Vote et al. (2003) reported correlations between CVS BeefCam lean a* and WBSF14 from -0.13 to -0.40, and between b* and WBSF14 in

the range of -0.12 to -0.38. Wulf et al (1997) found that b* showed the best correlation with WBSF14 (r= -0.38). When carcasses with pH>5.8 were not included in this analysis, the correlation between colorimeters readings and WBSF increased.

YO carcasses had greater correlations between lean color and pH_u than all carcasses (L*, r=-0.64; a*, r=-0.82; b*, r=-0.72; P<0.01), but neither color nor pH_u were correlated (P>0.05) with WBSF. Carcasses with pHu < 5.8 in YO, showed negative correlation between L* and WBSF14 (r=-0.34, P<0.05) and between a* and WBSF7 (r=-0.39, P<0.01). However, in OL carcasses, the correlation between color parameters and WBSF were higher and similar for both aging periods. The correlations with WBSF14 were -0.45, -0.58, and -0.48 for L*, a* and b*, respectively (P<0.01).

3.3. Relationship between intermediate pH_3 and color and tenderness.

No response (R^2 = 0.02) was observed between pH_3 and tenderness (WBSF7 and WBSF14). However, there is some evidence that a curvilinear relationship exists between early post-mortem pH and tenderness (Hwang and Thompson, 2001b; Pike et al., 1993; Marsh et al., 1987). Thus, based on pH_3, the carcasses were segregated into three classes, rapid glycolytic (RG: pH<5.8), intermediate gycolytic (IG: pH = 5.8-6.2) and slow glycolytic (SG: pH > 6.2). The entire carcass population showed the following distribution for pH_3 class: 53.4% in the IG class, 38% in the RG class and 8.6% in the SG class. The toughest steaks came from carcasses in IG class for both aging periods (WBSF 7 = 5.08 kg, and WBSF 14 = 4.26 kg, Table 3.8) and the IG steaks were different in tenderness (P<0.05) compared to RG steaks but not (P>0.05) compared to SG steaks.

Splitting this information by age (YO and OL), and analyzing all female carcasses, 62.26% of them in YO group were in RG, while 63.6% of the carcasses were in IG in OL group.

Tenderness differences were observed only in OL steaks for WBSF 7 and WBSF 14. Within OL group, the RG steaks were more tender than IG for WBSF 7 (P<0.05) and for WBSF 14 (P<0.01) (Table 3.8). For YO group, there were not differences (P>0.05) in tenderness between glycolytic classes. However the IG steaks were the toughest in both age groups. These results are not in agreement with the theory of Pike et al. (1993) that for optimum tenderness it is necessary to produce

an intermediate rate of glycolysis. However, Jones and Tatum (1994) reported that carcass with a pH_3 lower than 5.8 produced steaks with the highest incidence with tender ratings.

These glycolytic rate groups were related to the colorimeter parameters at ribbing (Table 3.9). For all the selected carcasses, RG group showed the highest values of L*, a* and b*, being different ($P<0.01$) to those for IG and SG groups.

3.4. Postmortem conditions for shortening

Locker and Hagyard (1963) showed that myofibrillar shortening occurred when pre-rigor muscle was held at either low or high temperatures, while Hwang and Thompson (2001) showed that the rate of pH decline had the largest effect on eating quality. The temperatures and pH measurements at 1 and 3 h were combined in their correspondent time to detect if any cold or heat shortening conditions were apparent. Only 4.3% of the total carcasses showed one of these combinations of pH and temperature for shortening. No differences ($P>0.05$) in WBSF7 and WBSF14 were detected between these animals in shortening conditions and the rest of the carcasses (data not shown)

3.5 Relationship between ultimate pH and tenderness and color

The relationship between pH_u and tenderness was quadratic (Fig 3.1). Responses in beef have been reported by Purchas, (1990), Jeremiah et al. (1991), and Purchas et al. (1999). Considering that the meat industry in Uruguay segregates carcasses based on $pH_u < 5.8$ for the export market, and the curvilinear response obtained between WBSF and pH_u, the same pH ranges utilized in pH_3**,** normal (N: $pH_u < 5.8$), moderate dark (MD: $pH_u = 5.8$-6.2) and DFD ($pH_u > 6.2$) were analyzed. The percentage of carcasses that had N pH_u was 86.5%, for all female carcasses (10.4% of carcasses in MD group and 3.1% of them in DFD group). From the 62% carcasses with $pH_3 \geq 5.8$, it can be assumed that 78.2% of these carcasses reached pH_u <5.8.

The toughest steaks were in the MD group for WBSF 7 (5.22 kg, SE=0.41) and WBSF 14 (4.45 kg, SE =0.33) (Table 3.10). Since the number of observations was very different among the pH_u groups, mean comparisons were not considered. However, the carcasses with $pH_u > 6.2$, classified as dry, firm and dark (DFD), appeared to be more tender (WBSF 7 = 3.33 kg, SE =0.76) than those from MD and N groups. WBSF 14 showed the same trend as WBSF 7 and results across age groups were

similar. Jeremiah (1991), Lawrie (1992), Dransfield (1994) and Silva et al. (1999) showed increases in tenderness associated with high pH_u in beef. Watanabe et al., (1996) and Beltrán et al. (1997) reported a higher rate of tenderization in DFD cuts. A possible explanation is that greater fragmentation of myofibrils and less cooking losses (higher water holding capacity) could result in higher tenderness in DFD than normal meat.

A curvilinear response was observed between pH_u and L* (R^2=0.12), a* (R^2=0.22) and b* (R^2=0.28) for the entire population (data not shown). The carcasses in N pH_u had higher color values than those in MD, and MD carcasses had higher values than carcasses in DFD (Table 3.11). Similar to the findings with pH_3, incorporating the effect of the age would allow separating by color in two pH_u groups, although the number of animals in DFD for YO (n=2) and OL (n=3), and in MD for YO (n=3) was not adequate to draw conclusions. The observed trends are concordant with the literature.

3.6. Relationship between color and tenderness

The response between colorimeter readings and WBSF 7 and WBSF 14 were also quadratic for a* (R^2=0.20) and b*(R^2=0.14) using inverse transformation for the data. Fig 3.2 shows the relationship between WBSF 7 and WBSF 14 with lean a*.

The study of blooming effect on the color parameters with one hour of ribeye exposure to the air showed that blooming had a greater effect on ($P<0.01$) a* and b* than L* parameters (Table 3.12). Within L* values, the change of color was significant ($P<0.05$) in OL group but it was not ($P>0.05$) in YO group. This comparison was made with transformed data.

Based on the correlation coefficients obtained between a* and WBSF, two a* classes were analyzed to determine the relationship between a* class with tenderness in this population. Carcasses were divided into groups with a* <20 and ≥ 20

The distribution across the two a* classes studied was 49.7% and 50.3% for the a* values < 20 and ≥ 20, respectively. As expected higher a* values corresponded to lower WBSF7 ($P<0.01$) and WBSF14 ($P<0.01$) compared to the WBSF7 and WBSF14 for steaks in a* < 20 group (Table 3.13). After eliminating the carcasses with $pH_u > 5.8$, the results were consistent (Table 3.13). These findings suggest that segregation of carcasses into tenderness groups may be viable combining pH_u

and color (a*). The observation that color measurements were better predictors of WBSF than muscle pH is in agreement with literature reports (Wulf et al., 1997) because color readings may be more repeatable than pH measurements and may be a better indicator of the rate of post-mortem pH decline. Measurement of pH is difficult to conduct at line speed and a variety of factors may negatively impact repeatability of this measurement (pH meter calibration, fat deposits, dirty probes, and cooler temperatures). In this study lean a* was a more practical tool to segregate a group of carcasses by tenderness as we observe in Fig 3.3 (WBSF 7) and 3.4 (WBSF 14). As WBSF 7 and WBSF 14 increased, a* values in the range of 2 to 7.8 kg decreased significantly. The WBSF values in the range of 2 to 4.2 kg were different ($P<0.05$) from the range 4.2-5.4 kg and ($P<0.01$) from 5.4 to 9 kg (data not shown). This supports the previously analyzed threshold for a* (a*< 20) to distinguish tender from tough streaks**.**

3.7. Regression analyses

Simple and multiple linear regression equations were developed to predict the WBSF values using INAC grade factors, USDA yield and quality grade factors, pH, temperature and color.

The Uruguayan grading system considers the dentition as a factor to differentiate quality attributes of meat; however, Lawrence et al (2001b), and Wyhtes and Shorthose (1991) did not find significant differences in WBSF and sensory panel tenderness among the five dental classes. Based on those, it was of interest to analyze the ability of the USDA quality grading system into predict WBSF 7 and WBSF 14 in Uruguayan cattle. Lean and overall maturity were the first variables to enter into the regression model (for all female carcasses) and accounted for 15 % and 23% of the observed variation in WBSF 7 and WBSF 14, respectively (Table 3.14). Vote et al. (2003) reported that this variable explained 6 to 8% of the WBSF variation in two different experiments. MARB explained an additional 1 to 3% of the WBSF variation in the different models with the exemption of YO carcasses where it accounted for 5% of the observed variation in WBSF 7 and was the best single variable model. The literature reported that the relationship between MARB and WBSF depends on the range of marbling scores considered in each specific study. Some authors (Smith et al., 1984; Shackelford et al., 1994) observed that tenderness increased with the levels of MARB, while Wulf et al. (1996) and

Vote et al. (2003) did not find any relationship between MARB and WBSF in mostly USDA Select carcasses. Wulf and Page (2000) and Vote et al. (2003) observed R^2 in the range of 0.03 to 0.11 for these variables when evaluating Choice and Select carcasses.

In Table 3.15, multiple linear regression models using stepwise selection were developed considering all the variables measured. The color parameters (L*, a* and b*) and QG entered consistently into the models for predicting WBSF 7 and WBSF 14 for all and OL carcasses. The variable explaining most of the observed tenderness variation was a* (32-33% of WBSF variation). According to both correlation and regression analyses, it appears that a* (the red and green spectrum) is more useful than the other colorimeter readings. This could be explained by the lower levels of a* in Uruguayan carcasses compared with American carcasses reflecting either more myoglobin concentration (age and grass-fed diet) or more surface metmyoglobin formation. In the model for 8 teeth carcasses and 7 days of aging, a* after blooming entered first. When this variable (a*b) was removed from the model it was replaced by a*. This supports the concept that blooming was not required to develop tenderness prediction equations. For WBSF 14 in YO carcasses, there was some deviation in the prediction equation with luminance (L*), pH_1, and MARB accounting for 30% of the variation. Vote et al. (2003) reported that a* explained singularly 16% of the WBSF 14 variation in one experiment using Select and Choice carcasses. However, these authors also reported that b* accounted for 14% of the observed WBSF variation in a similar experiment.

Based on stepwise regression analysis and the correlations between independent and dependent variables, an equation using a* and pH_u and their quadratic term along with USDA quality grade was tested as a predictor of tenderness. Table 3.16 shows the results of regression analysis (adj-$R^{2=}$adjusted R^2 and RMSE=root mean square error) for the different ages considered in this study as well for the carcasses with $pH_u < 5.8$ for each age group.

The model with higher adj-R2 corresponded to all and 8 teeth carcass groups for both WBSF 7 and WBSF 14 and included the variables QG, a*, a^{*2}, pH_u and pH_u^2 (model 1). When the carcasses with $pH_u > 5.8$ (12% of the total) were not considered, all carcass groups had similar adj-R^2 (Table 3.16).

For model 2 (a*, a^{*2}, pH_u and pH_u^2) WBSF 7 was predicted nearly as well as the model containing QG; however QG had a greater impact on the prediction of WBSF 14 as evidenced by the lower adj-R^2 for model 2 versus 1. Neither model accurately predicted WBSF 7 or WBSF 14 for young carcasses (0-4 teeth). It appears that for YO carcasses a model considering other colorimeter reading such as L* would need to be developed.

Based on this information the best model for this population was model 1 and further analyses were run to determine the accuracy in sorting carcasses into tenderness categories.

The predicted WBSF 7 model was:

$WBSF7 = -87.654-0.0025(QG)-0.4426(a^*)+0.0023(a^*)^2+36.9508(pH_u)-3.3617(pH_u)^2$,

and for WBSF 14 prediction it was:

$WBSF14= -59.6171-0.0033(QG)-0.3745(a^*)+0.003(a^*)^2+26.1413(pH_u)-2.3938(pH_u)^2$

The Figures 3.5 and 3.6 show the relationship between the actual and the predicted WBSF at 7 and 14 days of aging. For WBSF 7, the simple regression equation had an $R^2 = 0.37$ and the R^2 for WBSF 14 equation was 0.40 between actual and predicted tenderness measures.

3.8. Contingency tables

Correlation coefficients are commonly used to estimate model accuracy; however they are poor measures of accuracy due to the bias of sample variability. Therefore, contingency tables were constructed to determine the accuracy of the above mentioned models used to predict WBSF and sort carcasses by level of tenderness. This estimate of the accuracy is based on a true positive fraction (TP: tender) or animals correctly predicted according to the specified category plus true negative fraction (TN: tough) or animals correctly predicted in the tough category. Sensitivity and specificity represent two kinds of accuracy. The first for actual positive cases and the second for actual negative cases. Both are expressed as a percentage of the observations.

The thresholds of WBSF defined for this analysis were 4.5 and 3.4 kg. Shackelford et al. (1991) published the first threshold relating WBSF values to consumer data and reported that the transition between tough and tender occurred at 4.5 kg. This was confirmed later by Miller et al (2001) who found an average transition of 4.6 kg. These authors also reported a threshold for

consumer acceptability for beefsteak tenderness of 3.4 kg in order to obtain a 99% consumer satisfaction.

For this analysis, the model was used for all female carcasses since the difference in adj-R^2 was low (Table 3.16). The prediction accuracy for WBSF 7 (Table 3.17) and WBSF 14 (Table 3.18) using both thresholds (4.5 and 3.4 kg) was higher than 70%. In the WBSF 7 prediction, the model showed a better accuracy (79.5%) using the threshold of 3.4 kg. The specificity for predicting WBSF7 <3.4 was high (96.7%), but the sensitivity was very low (20%). The same trend was true for a threshold of 4.5 kg (83.6 and 69.7%, respectively). In both cases the procedure was more efficient in detecting the tough steaks than the tender ones (Table 3.17).

When predicting WBSF 14 using the 3.4-kg threshold value, specificity was high (88.5%) again showing that the model accurately identified tough steaks; however, sensitivity may be more important than specificity to identify as many tender steaks in the population as possible. This was obtained with the threshold = 4.5 kg, where sensitivity was 83.2% and specificity was 69.8%.

4. Implications

This research gives the Uruguayan beef industry a snapshot of its female beef carcass population in terms of longissimus muscle pH, temperature and color in a commercial scenario. These variables are known to be related to postmortem processes and have potential for predicting beef tenderness. The Uruguayan grading system utilizes dentition as a variable to differentiate meat quality. However, within young categories (0-4 teeth) this variable can not distinguish carcasses by tenderness differences. Colorimeter readings (lean a*) on beef longissimus muscle were shown to be useful predictors of tenderness. There appears to be a threshold of approximately 20 for lean a*, above which carcasses have lower WBSF values and lower pH_u. In addition, models including lean a*, pH_u, and USDA quality grade were assessed by this study as classifiers of beef tenderness. The inclusion of USDA quality grade into the prediction model accounted for an additional 3 to 9% of the WBSF 7 and WBSF 14 variation, respectively. Thus it appears that these measurements of color (a*) and pH_u, could be used by the National (Uruguayan) Institute of Meat Board and in branded-beef programs to increase the tenderness consistency of Uruguayan beef products.

Literature cited

Beltrán, J.A., I. Jaime, P. Santolaria, C. Sañudo, P. Albertí, and P. Roncalés. 1997. Effect of stress-induced high post-mortem pH on protease activity and tenderness beef. Meat Sci. 45(2):201-207.

Bowling, R.A., G.C. Smith, T.R. Dutson, Z.L. Carpenter, and W.M. Oliver. 1977. Comparison of beef finished on forage versus grain. J. Anim. Sci. 45:209-215.

Cannell, R.C., K.E. Belk, C.D. Bunting, J.D. Tatum, and G.C. Smith. 1997. Ability of the Hunterlab color vision system to augment grading accuracy and to predict tenderness of beef. Proc. Recip. Meat Conf. 50:158.

C.I.E., 1986. Colorimetry (2nd ed.) Commission International de l'Éclairage, Publication CIE 15.2. Vienna: CIE.

Dransfield, E. 1994. Tenderness of meat, poultry and fish. In A.M. Pearson and T.R. Dutson (Eds), *Quality attributes and their measurement in meat, poultry and fish products.* Advances in meat research series vol. 9 (pp. 289-315). London: Blackie Academic and Professional.

Hedrick, H.B., E.D. Aberle, J.C. Forrest, M.D. Judge, and R.A. Merkel. 1994. Principles of Meat Science. 3rd ed. Kendall/Hunt Publishing Company, Dubuque, IA.

Hwang, I.H., and J.M. Thompson. 2001. The interaction between pH and temperature decline early post-mortem on the calpain system and objective tenderness in electrically stimulated beef *longissimus dorsi* muscle. Meat Sci. 58:167-174.

I.N.A.C. (1997). Sistema oficial (uruguayo) de clasificación y tipificación de carne vacuna. Resolución 65/97. Montevideo, Uruguay.

Issanchou, S. 1996. Consumer expectations and perceptions of meat and meat product quality. Meat Sci. 43 (S):S5-S19.

Jeremiah, L.E., A.K. Tong, and L.L. Gibson. 1991. The usefulness of muscle color and pH for segregating beef carcasses into tenderness groups. Meat Sci. 30: 97-114.

Jones, B.K. and J.D. Tatum. 1994. Predictors of beef tenderness among carcasses produced under commercial conditions. J. Anim. Sci. 72:1492-1501.

Laurent, K.M.,M.M. Pike, T.D. Bidner, A.M. Saxton, and A.M. McMillin. 1991. Effect of subcutaneous fat removal and aging on beef tenderness. J. Anim. Sci. 69(Suppl.2):19.

Lawrence, T.E., J.D. Whatley, T.H. Montgomery, and L.J. Perino. 2001a. A comparison of the USDA ossification-based maturity system to a system based on dentition. J. Anim. Sci. 79:1683-1690.

Lawrence, T.E., J.D. Whatley, T.H. Montgomery, L.J. Perino, and M.E. Dikeman. 2001b. Influence of dental carcass maturity classification on carcass traits and tenderness of *longissimus* steaks from commercially fed cattle. J. Anim. Sci. 79:2092-2096.

Lawrie, R. 1992. *The chemistry of muscle based foods*. Eds. E.Ledward, D. Johnston, and M. Knight. (pp 43-46). Royal Society of Chemistry, Cambridge, UK.

Ledward, D.A. 1992. Color of the raw and cooked meat. In D.E. Johnston, M. Knight, and D.A. Ledward. *The chemistry of muscle based foods*. Cambridge, UK:Royal Society of Chemistry .pp:128-144.

Locker, R.H., and C.J. Hagyard. 1963. A cold shortening effect in beef muscles. J. Sci. Food and Agr. 14:787-793.

Marsh, B.B., T.P. Ringkob, R.L. Russell, D.R. Swartz, and L.A. Pagel. 1987. Effects of early-postmortem glycolytic rate on beef tenderness. Meat Sci. 21:241-248.

Miller, M.F., M.A. Carr, C.B. Ramsey, K.L. Crockett, and L.C. Hoover. 2001. Consumer thresholds for establishing the value of beef tenderness. J. Anim. Sci. 79:3062-3068.

Page, J.K., D.M. Wulf, and T.R. Schwotzer. 2001. A survey of beef muscle color and pH. J. Anim. Sci. 79:678-687.

Pike, M.M., T.P. Ringkob, D.D. Beekman, Y.O. Koh, and W.T. Gerthoffer. 1993. Quadratic relationship between early post-mortem glycolytic rate and beef tenderness. Meat Sci. 34:13-26.

Purchas, R.W. 1990. An assessment of the role of pH differences in determining the relative tenderness of meat from bulls and steers. Meat Sci. 27:129-140.

Purchas, R. W., X. Yan, and D.G. Hartley. 1999. The influence of a period of aging on the relationship between ultimate pH and shear values of beef *m. longissimus thoracis.* Meat Sci. 51:135-141.

Shackelford, S.D., J.B. Morgan, H.R. Cross, and J.W. Savell. 1991. Identification of threshold levels for Warner-Bratzler shear force in beef top loin steaks. J. Muscle Foods 2:289-296.

Shackelford, S.D., M. Koohmaraie, and T.L. Wheeler. 1994. The efficacy of adding a minimum adjusted fat thickness requirement to the USDA beef quality grading standards for select grade beef. J. Anim. Sci. 72:1502-1507.

Shackelford, S.D., M. Koohmaraie, L.V. Cundiff; K.E. Gregory, G.A. Rohrer, and J.W. Savell. 1994. Heritabilities and phenotypic and genetic correlations for bovine postrigor calpastatin activity, intramuscular fat content, Warner-Bratzler shear force, retail product yield and growth rate. J. Anim. Sci. 72:857-863.

Silva, J.A., L. Patarata, and C. Martins. 1999. Influence of ultimate pH on bovine meat tenderness during aging. Meat Sci. 52:453-459.

Smith, G.C., Z.L. Carpenter, H.R. Cross, C.E. Murphey, H.C. Abrahan, J.W. Savell, G.W. Davis, B.W. Berry, and F.C. Parrish Jr. 1984. Relationship of USDA marbling groups to palatability of cooked beef. J. Food Qual. 7:289-308.

Tatum, J.D., G.C. Smith, and Z.L. Carpenter. 1982. Interrelationships between marbling, subcutaneous fat thickness and cooked beef palatability. J. Anim. Sci. 54:777-784.

USDA. 1997. Official United States standards for grades of carcass beef. Agric. Marketing Serv., USDA, Washington, DC.

Vote, D.J., K.E. Belk, J.D. Tatum, J.A. Scanga, and G.C. Smith. 2003. Online prediction of beef tenderness using a computer vision system equipped with a BeefCam module. J. Anim. Sci. 81:457-465.

Watanabe, A., C.C. Daly, and C.E. Devine. 1996. The effects of the ultimate pH of meat on tenderness changes during aging. Meat Sci. 42(1):67-78.

Wulf, D.M., J.B. Morgan, J.D. Tatum, and G.C. Smith. 1996. Effects of animal age, marbling score, calpastatin activity, subprimal cut, calcium injection, and degree of doneness on the palatability of steaks from Limousin steers. J. Anim. Sci. 74: 569-576.

Wulf, D.M., S.F. O'Connor, J. D. Tatum, and G. C. Smith. 1997. Using objective measures of muscle color to predict beef *longissimus* tenderness. J. Anim. Sci. 75:684-692.

Wulf, D.M. and J.K. Page. 2000. Using measurements of muscle color, pH, and electrical impedance to augment the current USDA beef quality grading standards and improve the accuracy and precision of sorting carcasses into palatability groups. J. Anim. Sci. 78:2595-2607.

Wulf, D.M., R.S. Emnett, J.M. Leheska, and S.J. Moeller. 2002. Relationships among glycolytic potential, dark cutting (dark, firm, and dry) beef, and cooked beef palatability. J. Anim. Sci. 80:1895-1903.

Wyle, A.M., D.J. Vote, D.L. Roeber, R.C. Cannell, K.E. Belk, J.A. Scanga, M. Goldberg, J.D. Tatum, and G.C. Smith. 2003. Effectiveness of the SmartMV prototype BeefCam system to sort beef carcasses into expected palatability groups. J. Anim. Sci. 81:441-448.

Wythes, J.R., and W.R. Shorthose. 1991. Chronological age and dentition effects on carcass and meat quality of cattle in northern Australia. Aust. J. Exp. Agric. 31:145-152.

Table 3.1 Definition of variables

Variable	Definition
Con	INAC Conformation 1=I (best conf.) to 6=R (worst conf.)
Fin	INAC Finishing 0=low fat to 3=high fat
Dentition	Dentition 0, 2, 4, 6, 8 teeth
HCW	Hot carcass weight (kg)
FAT	Subcutaneous fat between 10-11th rib (cm)
YG	USDA Yield grade (1 to 5)
Lean mat.	Lean maturity 0=A^{00}, 100=B^{00}, 200=C^{00} , 300=D^{00} , 400=E^{00}
Skeletal mat.	Skeletal maturity 0=A^{00}, 100=B^{00}, 200=C^{00} , 300=D^{00} , 400=E^{00}
Overall mat.	Overall maturity 0=A^{00}, 100=B^{00}, 200=C^{00} , 300=D^{00} , 400=E^{00}
MARB	Marbling score 100=Practically devoid^{00}, 200=Traces^{00}, 300=Slight^{00}, 400=Small^{00}, 500= Modest^{00}, 600=Moderate^{00}, 700=Sl.abundant^{00}, 800=Mod. abundant^{00}
QG	USDA Quality grade 200=Cutter^{00}, 300=Utility^{00}, 400=Commercial^{00}, 500=Standard^{00}, 600=Select^{00},700=Choice^{00}, 800=Prime^{00}
REA	Ribeye area (cm^2)
pH_1 pH_3 pH_u	pH at 1, 3, 18-24 h postmortem
T_1 T_3 T_u	Temperature at 1, 3, 18-24 hs postmortem (^{o}C)
L*	Luminance 0=black to 100= white
a*	+60= red to –60=green
b*	+60= yellow to –60=blue
Lb* ab* bb*	L*, a*, b*with 1 h of blooming time after ribbing
WBSF 7	Warner-Bratzler shear force with 7 days of aging (kg)
WBSF 14	Warner-Bratzler shear force with 14 days of aging (kg)

Table 3.2 Mean and Standard deviation of main variables in all, 0-4, and 8 teeth female carcasses

	All carcasses		Carcasses 0-4 teeth		Carcasses 8 teeth	
Variable	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Con	3.26	0.51	3.00	0.28	3.39	0.54
Fin	1.83	0.44	1.85	0.36	1.82	0.47
Dentition	5.89	3.17	1.51	1.51	8	
HCW	205.74	31.67	179.10	14.32	214.07	31.55
FAT	8.60	4.57	8.58	3.77	8.5	4.77
YG	2.97	0.58	2.99	0.56	2.95	0.60
Lean mat.	157.10	107.71	67.00	41.39	197.36	103.26
Skeletal mat.	252.14	160.2	63.55	39.75	341.09	113.29
Overall mat.	219.32	130.43	66.00	39.10	290.55	93.86
MARB	332.82	79.38	323.40	77.40	337.36	80.26
QG	400.61	141.2	560.46	76.00	327.27	99.46
REA	47.47	7.32	47.31	6.45	47.54	7.72
pH_1	6.15	0.28	6.03	0.24	6.21	0.29
pH_3	5.92	0.28	5.77	0.26	5.99	0.26
pH_u	5.63	0.25	5.61	0.29	5.65	0.22
T_1	32.87	3.53	31.55	3.34	33.55	3.45
T_3	20.95	4.80	19.61	3.93	21.64	5.07
T_u	3.19	1.15	3.31	1.36	3.13	1.03
L*	31.32	3.70	33.16	3.51	30.37	2.32
a*	19.87	2.85	20.56	2.88	19.52	2.79
b*	9.15	2.08	10.21	2.34	8.61	1.71
Lb*	32.19	2.98	34.37	3.53	31.33	2.23
ab*	22.27	3.04	23.11	3.45	21.87	2.76
bb*	10.87	2.20	12.02	2.72	10.33	1.68
WBSF7	4.67	1.72	4.06	1.28	4.98	1.82
WBSF14	3.96	1.39	3.27	0.89	4.30	1.46

Table 3.3 Frecuency of all carcasses in each USDA quality factor (overall maturity, marbling and quality grade)

Ov. Mat	Perc. (%)	Marbling	Perc. (%)	Quality grade	Perc. (%)
A	31.30	**Pr. Devoid**	1.20	**Cutter**	8.00
B	8.60	**Traces**	30.10	**Utility**	47.20
C	28.80	**Slight**	57.70	**Commercial**	4.90
D	21.50	**Small**	6.80	**Standard**	19.00
E	9.80	**Modest**	1.80	**Select**	18.50
		Moderate	1.20	**Choice**	1.80
		Slight Ab.	1.20	**Prime**	0.60

Table 3.4 Mean, Standard Error in ( ) and level of significance between groups (YO, n=53 vs. OL, n=110)

Variable	YO (≤ 4 teeth)		OL (8 teeth)		Sig. Level
HCW	179.10	(4.24)	214.10	(2.65)	<0.01
FAT	8.60	(0.69)	8.50	(0.43)	NS
Lean mat.	67.00	(14.29)	197.40	(8.95)	<0.01
Skeletal mat.	63.25	(14.93)	341.10	(9.33)	<0.01
Overall mat.	66.51	(12.42)	290.54	(7.76)	<0.01
MARB	322.33	(12.40)	337.36	(7.75)	NS
QG	560.46	(24.26)	327.27	(8.91)	<0.01
pH_1	6.03	(0.04)	6.21	(0.03)	<0.01
pH_3	5.77	(0.04)	5.99	(0.03)	<0.01
pH_u	5.61	(0.03)	5.65	(0.02)	NS
T_1	31.38	(0.51)	33.54	(0.33)	<0.01
T_3	19.60	(0.71)	21.64	(0.46)	<0.05
T_u	3.22	(0.17)	3.13	(0.11)	NS
L*	33.56	(0.40)	30.37	(0.26)	<0.01
a*	20.59	(0.42)	19.52	(0.27)	<0.05
b*	10.37	(0.29)	8.61	(0.18)	<0.01
Lb*	34.37	(0.40)	31.33	(0.25)	<0.01
ab*	23.05	(0.44)	21.87	(0.27)	<0.05
bb*	12.18	(0.31)	10.33	(0.19)	<0.01
WBSF7	4.06	(0.26)	4.98	(0.16)	<0.01
WBSF14	3.27	(0.20)	4.30	(0.13)	<0.01

Table 3.5 Means, Standard Error in ( ) and mean comparison among HCW < 215 kg groups (1: YO, ≤ 7mm; 2: YO, > 7mm; 3: OL, ≤ 7mm; 4: OL, > 7mm).

Variable	**1** (n=19)	**2** (n=24)	**3** (n=30)	**4** (n=27)
Lean mat.	85.00 ^{d}	55.00 ^{d}	231.80 ^{a}	181.20 ^{b}
	(20.73)	(16.93)	(15.67)	(16.26)
Skeletal mat.	73.16 ^{d}	55.42 ^{d}	363.55 ^{a}	337.41 ^{a}
	(20.68)	(18.41)	(16.19)	(17.35)
MARB	288.42 ^{c}	349.17 ^{a}	303.87 ^{bc}	340.74 ^{ab}
	(16.60)	(14.77)	(13.00)	(13.93)
QG	515.79 ^{c}	595.83 ^{a}	296.77 ^{f}	344.44 ^{e}
	(20.46)	(18.20)	(16.01)	(17.16)
pH_1	6.13 ^{ab}	5.95 ^{c}	6.19 ^{a}	6.13 ^{a}
	(0.05)	(0.05)	(0.04)	(0.05)
pH_3	5.84 ^{ab}	5.71 ^{c}	5.96 ^{a}	5.92 ^{a}
	(0.05)	(0.05)	(0.04)	(0.05)
pH_u	5.68 ^{ab}	5.55 ^{b}	5.71 ^{a}	5.57 ^{b}
	(0.05)	(0.05)	(0.04)	(0.04)
T_1	31.72	31.11	32.58	32.87
	(0.69)	(0.62)	(0.55)	(0.61)
T_3	20.03 ^{ab}	19.26 ^{b}	20.77 ^{ab}	20.87 ^{a}
	(0.80)	(0.71)	(0.64)	(0.71)
T_u	3.27	3.18	2.94	3.16
	(0.27)	(0.25)	(0.22)	(0.25)
L*	32.50 ^{b}	34.40 ^{a}	30.25 ^{d}	30.86 ^{cd}
	(0.62)	(0.55)	(0.49)	(0.55)
a*	19.69 ^{abc}	21.31 ^{a}	18.90 ^{c}	19.17 ^{c}
	(0.62)	(0.55)	(0.50)	(0.56)
b*	9.78 ^{bc}	10.82 ^{a}	8.50 ^{c}	8.75 ^{c}
	(0.47)	(0.42)	(0.37)	(0.42)
Lb*	33.20 ^{b}	35.34 ^{a}	31.33 ^{d}	31.80 ^{cd}
	(0.62)	(0.56)	(0.49)	(0.52)
ab*	21.98 ^{bc}	23.95 ^{a}	21.51 ^{c}	22.09 ^{bc}
	(0.67)	(0.61)	(0.53)	(0.57)
bb*	11.31 ^{bc}	12.90 ^{a}	10.42 ^{c}	10.73 ^{bc}
	(0.50)	(0.45)	(0.39)	(0.42)
WBSF7	4.08 ^{bc}	4.04 ^{c}	5.25 ^{a}	4.71 ^{abc}
	(0.36)	(0.32)	(0.28)	(0.30)
WBSF14	3.41 ^{cd}	3.16 ^{d}	4.42 ^{a}	4.24 ^{ab}
	(0.27)	(0.24)	(0.21)	(0.23)

^{a,b,c,d,e,f} Means in the same row bearing a common superscript letter are not significantly different (P<0.05)
Means in the same row with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 3.6 Means, Standard Error in ( ) and mean comparison among 8 teeth groups (1: < 215 kg , ≤ 7mm; 2: < 215 kg , > 7mm; 3: ≥ 215 kg, ≤ 7mm; 4: ≥ 215 kg, > 7mm).

Variable	**1** (n=30)	**2** (n=27)	**3** (n=23)	**4** (n=30)
Lean mat.	231.79 ^{a}	181.19 ^{abc}	224.21 ^{ab}	161.03 ^{cd}
	(18.94)	(19.66)	(23.00)	(18.62)
Skeletal mat.	363.55	337.41	341.36	321.00
	(20.42)	(21.88)	(24.24)	(20.76)
MARB	303.87 ^{cd}	340.74 ^{bc}	307.27 ^{cd}	391.00 ^{a}
	(13.06)	(13.99)	(15.51)	(13.28)
QG	296.77 ^{b}	344.44 ^{a}	318.18 ^{ab}	350.00 ^{a}
	(17.65)	(18.91)	(20.96)	(17.94)
pH_1	6.19 ^{bc}	6.13 ^{c}	6.16 ^{bc}	6.33 ^{a}
	(0.05)	(0.06)	(0.06)	(0.05)
pH_3	5.97 ^{ab}	5.92 ^{b}	5.98 ^{ab}	6.07 ^{a}
	(0.05)	(0.05)	(0.06)	(0.05)
pH_u	5.71 ^{a}	5.57 ^{b}	5.70 ^{a}	5.62 ^{ab}
	(0.04)	(0.04)	(0.05)	(0.04)
T_1	32.58 ^{c}	32.88 ^{c}	32.13 ^{c}	35.95 ^{a}
	(0.57)	(0.64)	(0.71)	(0.61)
T_3	20.77 ^{b}	20.87 ^{b}	20.18 ^{bc}	24.05 ^{a}
	(0.89)	(0.99)	(1.12)	(0.89)
T_u	2.94	3.16	2.96	3.39
	(0.19)	(0.21)	(0.24)	(0.19)
L*	30.25	30.86	29.54	30.63
	(0.27)	(0.38)	(0.26)	(0.38)
a*	18.90 ^{c}	19.17 ^{bc}	18.80 ^{c}	20.89 ^{a}
	(0.49)	(0.55)	(0.62)	(0.49)
b*	8.50	8.75	8.19	8.88
	(0.31)	(0.35)	(0.40)	(0.31)
Lb*	31.33	31.80	30.86	31.26
	(0.40)	(0.43)	(0.48)	(0.41)
ab*	21.51	22.09	21.50	22.30
	(0.50)	(0.53)	(0.60)	(0.51)
bb*	10.42	10.73	10.03	10.10
	(0.30)	(0.32)	(0.36)	(0.31)
WBSF7	5.25	4.71	5.41	4.64
	(0.33)	(0.35)	(0.39)	(0.33)
WBSF14	4.42	4.24	4.67	3.97
	(0.26)	(0.28)	(0.31)	(0.27)

^{a,b,c,d} Means in the same row bearing a common superscript letter are not significantly different ($P<0.05$)
Means in the same row with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 3.7 Main simple correlations between carcass variables and tenderness and color for all female carcasses

Variable	WBSF7	WBSF14	Variable	L*	a*	b*
Lean mat.	0.38**	0.47**	**Dentition**	- 0.55**	- 0.27**	- 0.50**
Skeletal mat.	0.30**	0.43**	**Lean mat.**	- 0.72**	- 0.56**	- 0.65**
MARB	- 0.17*	- 0.19*	**QG**	0.51**	0.36**	0.45**
QG	- 0.35**	- 0.48**	**pH_1**	- 0.49**	- 0.26**	- 0.43**
pH_3	0.24**	0.27**	**pH_3**	- 0.50**	- 0.34**	- 0.49**
pH_u	0.25**	0.25**	**pH_u**	- 0.38**	- 0.47**	- 0.46**
L*	- 0.40**	- 0.51**				
a*	- 0.57**	- 0.57**				
b*	- 0.48**	- 0.52**				

** Significative at 1%

* Significative at 5%

Table 3.8 Means, Standard error in ( ) and mean comparison between pH_3 classes and WBSF values

	All females		Females 0-4 teeth		Females 8 teeth	
pH_3	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**
< 5.8	4.06 [c]	3.52 [c]	3.98	3.39	4.14 [b]	3.68 [c]
	(0.21)	(0.17)	(0.22)	(0.15)	(0.33)	(0.26)
5.8 – 6.2	5.08 [a]	4.26 [a]	4.23	3.08	5.29 [a]	4.55 [a]
	(0.18)	(0.15)	(0.31)	(0.22)	(0.21)	(0.17)
> 6.2	4.78 [a]	4.00 [a]	3.03	2.58	5.26 [ab]	4.38 [abc]
	(0.44)	(0.36)	(0.73)	(0.51)	(0.53)	(0.43)

[a,b,c,] Means in the same column bearing a common superscript letter are not significantly different ($P<0.05$)
Means in the same column with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 3.9 Means, and mean comparisons between pH_3 classes and color (L*, a*, b*)

	All females			Females 0-4 teeth			Females 8 teeth		
pH_3	**L***	**a***	**b***	**L***	**a***	**b***	**L***	**a***	**b***
< 5.8	33.18 [a]	21.50 [a]	10.56 [a]	33.97 [a]	21.56 [a]	10.96 [a]	32.00 [a]	21.51 [a]	9.94 [a]
5.8 – 6.2	30.72 [c]	19.30 [c]	8.60 [c]	32.97 [a]	20.13 [ab]	9.74 [c]	30.20 [bc]	19.10 [c]	8.36 [c]
> 6.2	27.70 [e]	16.90 [e]	6.90 [e]	25.38 [c]	12.06 [d]	4.54 [d]	28.34 [e]	18.25 [c]	7.55 [c]

[a,b,c,d,e] Means in the same column bearing a common superscript letter are not significantly different ($P<0.05$)
Means in the same column with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 3.10 Means, Standard error in ( ) and mean comparison between pH_u classes and WBSF values

	All females		Females 0-4 teeth		Females 8 teeth	
pH_u	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**
< 5.8	4.64 [ab]	3.93	4.05	3.28	4.95	4.27
	(0.14)	(0.17)	(0.18)	(0.13)	(0.19)	(0.15)
5.8 – 6.2	5.22 [a]	4.45	4.37	3.38	5.40	4.68
	(0.41)	(0.33)	(0.73)	(0.52)	(0.49)	(0.39)
> 6.2	3.33 [b]	3.10	2.45	2.27	3.91	3.65
	(0.76)	(0.62)	(0.89)	(0.63)	(1.05)	(0.84)

[a,b,c,] Means in the same column bearing a common superscript letter are not significantly different (P<0.05)
Means in the same column with one letter of difference differ (P<0.05)

Table 3.11 Means, and mean comparisons between pH_u classes and color (L*, a*, b*)

	All females			Females 0-4 teeth			Females 8 teeth		
pH_u	**L***	**a***	**b***	**L***	**a***	**b***	**L***	**a***	**b***
< 5.8	31.76 [a]	20.41 [a]	10.56 [a]	33.85 [a]	21.29 [a]	10.73 [a]	30.64 [a]	19.94 [a]	8.83 [a]
5.8 – 6.2	29.24 [c]	17.33 [c]	8.60 [c]	28.02 [c]	15.01 [c]	5.94 [c]	29.60 [a]	17.96 [b]	7.76 [b]
> 6.2	24.95 [e]	12.35 [e]	6.90 [e]	24.39 [c]	11.50 [d]	3.98 [d]	25.33 [c]	12.91 [d]	5.31 [c]

[a,b,c,d,e] Means in the same column bearing a common superscript letter are not significantly different ($P<0.05$)
Means in the same column with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 3.12.- Means and Standard error in ( ) for the blooming effect (1 h)

	L*	L*bloom	a*	a*bloom	b*	b*bloom
All age	30.87 [c]	33.63 [a]	20.73 [c]	21.84 [a]	9.50 [c]	11.14 [a]
	(0.19)	(0.27)	(0.22)	(0.31)	(0.15)	(0.22)
YO	33.16 [b]	34.01 [a]	20.56 [c]	21.87 [a]	10.20 [c]	12.02 [a]
	(0.38)	(0.38)	(0.40)	(0.40)	(0.28)	(0.28)
OL	30.77 [b]	31.33 [a]	19.52 [c]	21.86 [a]	8.61 [c]	10.33 [a]
	(0.27)	(0.26)	(0.29)	(0.28)	(0.20)	(0.19)

[a,b,c,] Means in the same row bearing a common superscript letter are not significantly different ($P<0.05$) for each variable independently. Means in the same row with one letter of difference differ ($P<0.05$), with more than one letter of difference differ for each variable ($P<0.01$)

Table 3.13 Means, and mean comparisons between WBSF and color (L*, a*, b*) for all female carcasses and carcasses with pH_u<5.8

	All carcasses			Carcasses pH<5.8		
a*	**n**	**WBSF 7**	**WBSF14**	**n**	**WBSF 7**	**WBSF14**
< 20	81	5.36 [a]	4.51 [a]	62	5.59 [a]	4.67 [a]
≥ 20	82	3.97 [c]	3.42 [c]	80	3.98 [c]	3.42 [c]

[a,c] Means in the same column with more than one superscript letter of difference differ (P<0.01)

Table 3.14 Multiple regression equations to predict WBSF 7 and WBSF 14 using USDA quality variables for all, 0-4 and 8 teeth carcasses

WBSF 7			**WBSF14**		
Independent variables	**R^2**	**RMSE**	**Independent variables**	**R^2**	**RMSE**
All carcasses					
Lean maturity	0.15	1.50	Overall maturity	0.23	1.18
Lean maturity, Marbling	0.16	1.49	Overall maturity, Skeletal maturity	0.26	1.16
			Overall mat., Skeletal mat., Marbl.	0.28	1.15
8 teeth carcasses					
Lean maturity	0.13	1.6	Lean maturity	0.14	1.28
			Lean maturity, Marbling	0.17	1.27
			Lean mat., Marbling, Overall mat.	0.19	1.26
0-4 teeth carcasses					
Marbling	0.05	1.28	Lean maturity	0.04	0.92

Models were developed using stepwise procedure. R^2= coefficient of determination. RMSE=root mean square error

Table 3.15 Multiple regression equations to predict WBSF 7 and WBSF 14 using yield and quality grades, pH, temperature and color for all, 0-4 and 8 teeth carcasses

WBSF 7			**WBSF14**		
Independent variables	**R^2**	**RMSE**	**Independent variables**	**R^2**	**RMSE**
All carcasses					
a*	0.32	1.35	a*	0.33	1.12
a*, QG	0.35	1.33	a*, QG	0.42	1.04
a*, QG, a*b	0.37	1.31	a*, QG, L*	0.43	1.03
a*, QG, a*b, pH_u	0.39	1.30	a*, QG, L*, b*	0.46	1.01
8 teeth carcasses					
a*b	0.32	1.42	a*	0.33	1.15
a*b, pH_u	0.36	1.39	a*, QG	0.39	1.11
a*b, pH_u, L*	0.41	1.35	a*, QG, L*	0.41	1.10
a*b, pH_u, L*, con.	0.43	1.33	a*, QG, L*, b*	0.43	1.09
0-4 teeth carcasses					
a*	0.18	1.17	L*	0.16	0.84
a*, marbling	0.25	1.13	L*, pH_1	0.26	0.80
			L*, pH_1, marbling	0.30	0.79

Models were developed using stepwise procedure. R^2= coefficient of determination.
RMSE=root mean square error

Table 3.16 Simple regression equations to predict WBSF 7 and WBSF 14 using selected variables by stepwise procedure for all, 0-4 and 8 teeth carcasses

Dependent variables	**WBSF 7**		**WBSF 14**	
Model 1 = QG, a*, a^{*2}, pH_u, pH_u^2				
	adj-R^2	**RMSE**	**adj-R^2**	**RMSE**
All carcasses	0.34	1.41	0.38	1.11
All carcasses pH_u<5.8	0.34	1.35	0.37	1.08
8 teeth carcasses	0.35	1.49	0.38	1.16
8 t. carcasses pH_u<5.8	0.30	1.46	0.34	1.15
0-4 teeth carcasses	0.11	1.20	-0.02	0.91
0-4 t. carcasses pH_u<5.8	0.10	1.20	-0.02	0.91
Model 2 = a*, a^{*2}, pH_u, pH_u^2				
	adj-R^2	**RMSE**	**adj-R^2**	**RMSE**
All carcasses	0.31	1.45	0.29	1.18
All carcasses pH_u<5.8	0.32	1.38	0.30	1.15
8 teeth carcasses	0.34	1.50	0.34	1.21
8 t. carcasses pH_u<5.8	0.29	1.47	0.29	1.20
0-4 teeth carcasses	0.10	1.21	0.003	0.90
0-4 t. carcasses pH_u<5.8	0.11	1.19	0.007	0.90

Models were developed using simple regression procedure. R^2= coef. of determination. RMSE=root mean square error

Table 3.17 Contingency table for WBSF 7 prediction using all female carcasses

Base line WBSF = 4.5 kg (n=156)		Base line WBSF = 3.4 kg (n=156)	
TPF n=62 39.74%	TNF n=56 35.90%	TPF n=7 4.50%	TNF n=117 75.00%
FNF n=27 17.31%	FPF n=11 7.05%	FNF n=28 17.95%	FPF n=4 2.55%
Accuracy= 75.64% (TPF+TNF) Sensitivity= 69.66% [TPF/(TPF+FNF)] Specificity= 83.59% [TNF/(FPF+TNF)]		Accuracy= 79.50% (TPF+TNF) Sensitivity= 20.04%[TPF/(TPF+FNF)] Specificity= 96.71%[TNF/(FPF+TNF)]	

Table 3.18 Contingency table for WBSF 14 prediction using all female carcasses

Base line WBSF = 4.5 kg (n=156)		Base line WBSF = 3.4 kg (n=156)	
TPF n=94 60.26%	TNF n=30 19.23%	TPF n=30 19.23%	TNF n=85 54.49%
FNF n=19 12.18%	FPF n=13 8.33%	FNF n=30 19.23%	FPF n=11 7.05%
Accuracy= 79.50% (TPF+TNF) Sensitivity= 83.19% [TPF/(TPF+FNF)] Specificity= 69.78% [TNF/(FPF+TNF)]		Accuracy= 73.72% (TPF+TNF) Sensitivity= 50.00% [TPF/(TPF+FNF)] Specificity= 88.54% [TNF/(FPF+TNF)]	

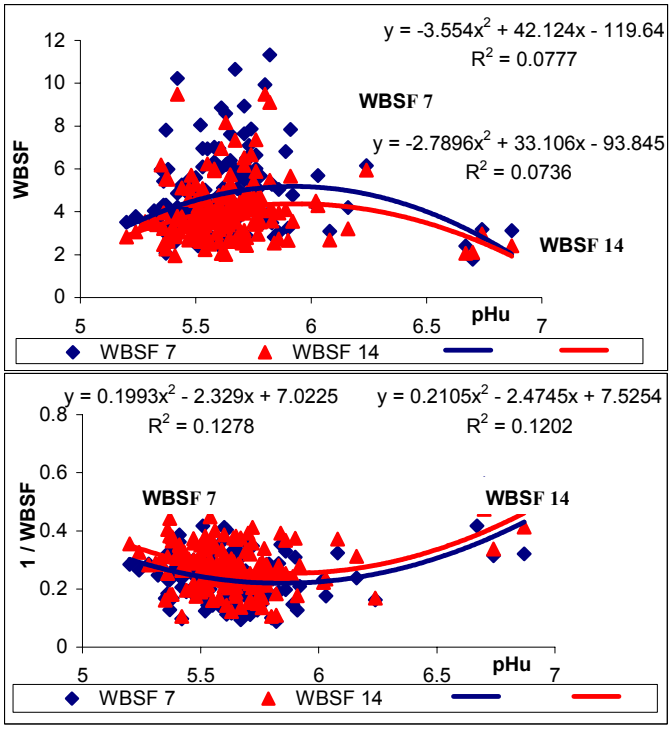

Fig 3.1 Quadratic response between WBSF (and 1/WBSF) and pH_u

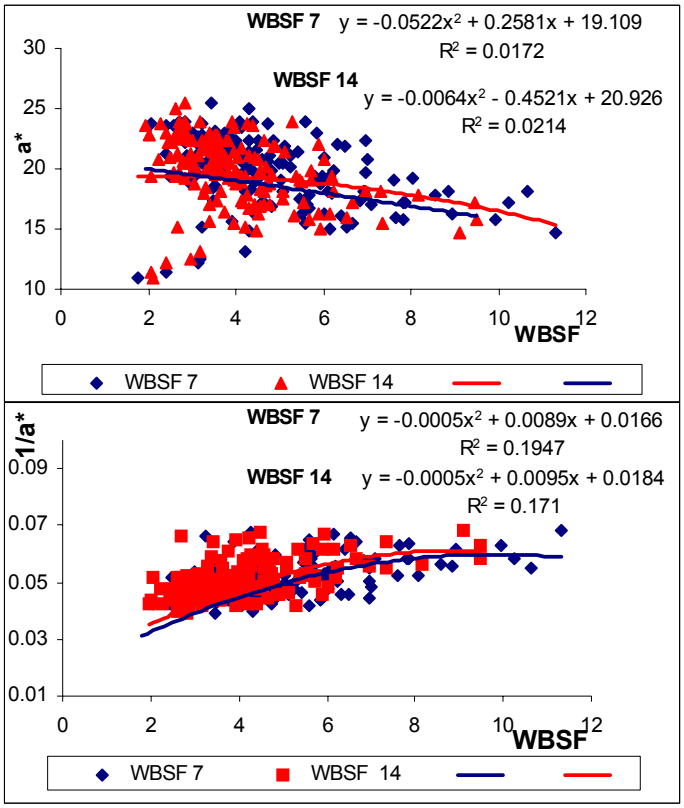

Fig 3.2 Quadratic response between a* (and 1/a*) and WBSF

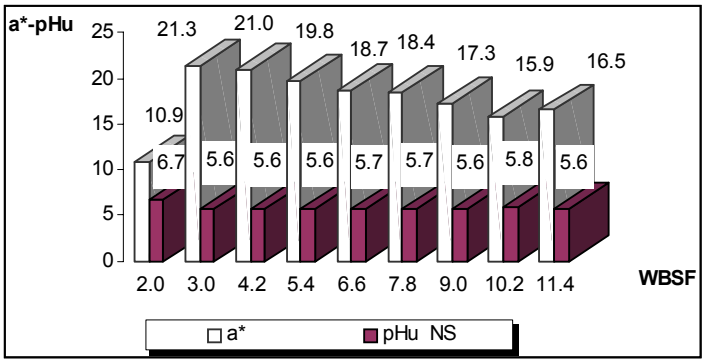

Fig 3.3 Lean a* and pH_u response with WBSF 7 values for all female carcasses

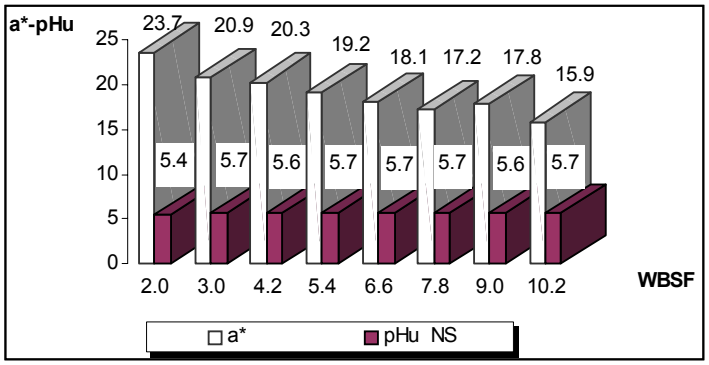

Fig 3.4 Lean a* and pH_u response with WBSF 14 values for all female carcasses

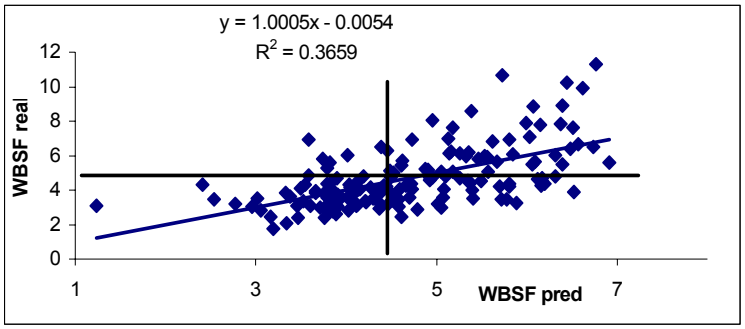

Fig 3.5 Relationship between WBSF 7 and predicted WBSF 7
(The horizontal and vertical lines correspond to WBSF = 4.5 kg)

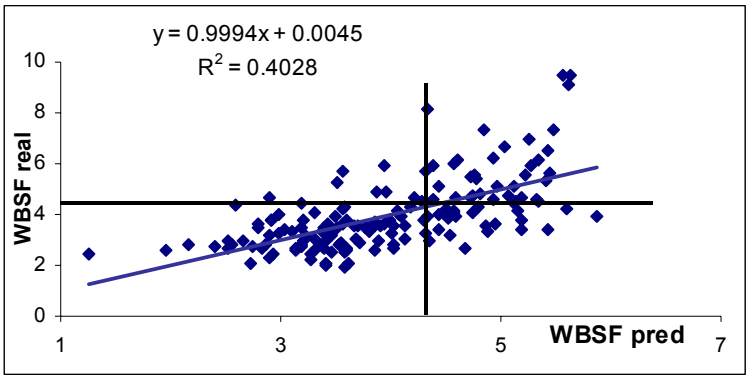

Fig 3.6 Relationship between WBSF 14 and predicted WBSF 14
(The horizontal and vertical lines correspond to WBSF = 4.5 kg)

CHAPTER 4

PREDICTING AND SEGREGATING BEEF TENDERNESS AMONG URUGUAYAN MALE CARCASSES UNDER COMMERCIAL CONDITIONS USING POSTMORTEM CARCASS TRAITS, pH, TEMPERATURE AND COLORIMETER READINGS [1]

[1] Brito, G., D. Pringle and D. J. Vote. To be submitted to Journal of Animal Science

Abstract

Male beef carcasses (n=174) processed under commercial procedures and selected to differ in weight, subcutaneous fat thickness and dentition were used to evaluate postmortem carcass traits and *longissimus dorsi* muscle pH, temperature and color as predictors of steak tenderness. Temperature (T_1, T_3 and T_u), pH (pH_1, pH_3 and pH_u) and colorimeter readings (L*, a* and b*) were collected postmortem. Longissimus muscle samples were removed from each carcass and Warner Bratzler shear forces were measured at 7 (WBSF7) and 14 days of aging (WBSF14). From the carcass traits evaluated, USDA yield grade (YG) showed a high correlation (r) with Warner Bratzler shear force at both aging periods (WBSF7, r= -0.22, and WBSF14, r= -0.22, $P<0.05$). The pH_u was correlated ($P<0.01$) with L*, a*, and b* values (r= -0.20, -0.44, and -0.32, respectively). The relationship between pH_u and 1/WBSF7 ($R^2=0.22$) and 1/WBSF14 ($R^2=0.15$) were quadratic Correlations of color measurements with tenderness measurements were higher than the correlations of USDA quality grade factors (QG) with tenderness measurements. Lean a* value showed the highest correlation with WBSF7 and WBSF14 (r= -0.47 and -0.40, respectively, $P<0.01$). Carcasses with pH_u < 5.8 or a* values ≥ 20 had lower ($P<0.01$) WBSF7 and WBSF14 than carcasses with pH_u 5.8-6.2 or a* values < 20. QG factors explained a small amount of tenderness variation in this population. Lean a* value accounted for 22 and 16% of WBSF7 and WBSF14 variation, respectively. A multiple linear regression equation was developed with this data using a* value and linear and quadratic pH_u. This model had an adjusted R^2 of 0.23 and 0.14 for WBSF7 and WBSF14, respectively. An accuracy of 76.7% and 88.3% for WBSF7 and WBSF14, respectively, was observed in predicting whether a steak would be classified as tender using a WBSF threshold of 3.4 kg. Measurements such as for pH_u and color (a*) taken at ribbing in Uruguayan commercial conditions would allow prediction of steak tenderness and segregation of male beef carcasses into tenderness groups.

Key Words: Beef, Male, Color, pH, Temperature, Tenderness

1. Introduction

In the food industry consumer-oriented quality approaches are becoming widely used considering the large development of marketing approaches. The perception of the quality can be defined prior to purchase (beliefs and attitudes), at the point of purchase (intrinsic and extrinsic cues) and upon consumption (sensory attributes). The National Beef Tenderness Survey conducted in the United States (1990), documented a relatively high incidence of toughness problems among different beef cuts for sale and identified the need to improve retail beef tenderness (George et al., 1999). The U.S. beef industry has made it a priority to address the inconsistencies in beef tenderness and has been developing strategies to ensure that all beef is acceptably tender. The development of tenderness based classification systems makes it possible to identify carcasses with superior tenderness and to add value to these carcasses that are undervalued in current systems. Studies have demonstrated that consumers consistently recognized differences in tenderness and are willing to pay for this attribute (Boleman et al., 1997). Most of these systems are based on the relationship between meat tenderness and muscle pH (Purchas, 1990; Jeremiah et al., 1991; Purchas et al., 1999; Silva et al., 1999; Wulf and Page, 2000), color (Jeremiah et al., 1991; Wulf et al., 1997; Wulf and Page, 2000; Wulf et al., 2002; Vote et al., 2003) and temperature (Lochner et al., 1980, Jones and Tatum, 1994) with meat tenderness.

This strategy to improve the consistency of meat palatability, primary through tenderness, is also followed by major meat export countries, such as Australia (Guarantee tenderness, MSA; Thompson, 2000) and New Zealand (NZ Beef and Lamb Quality Mark; Lawrence, 2002). Uruguay, as a meat export country should follow this principle of taking a tenderness diagnostic approach and applying the information to identifying the palatability critical control points along the meat chain. This study was conducted to determine if objective measures of muscle color, pH and temperature are useful to predict tenderness on selected male beef carcasses of unknown origin, and to determine if the application of USDA quality grading standards to Uruguayan beef carcasses could improve their segregation into tenderness categories.

2. Materials and Methods

A group of 174 male beef carcasses of unknown origin were selected at one packing plant in Uruguay, in May 2002. Carcasses were selected at the time of grading in Uruguay and they were not electrically stimulated. Carcasses were selected based on three age classes by dentition (0-2 teeth, n=38, 4 teeth, n=87, and 6-8 teeth, n=49). The reason to distinguish these three age classes was based on determining whether the current Uruguayan grading system could differentiate meat quality by this variable. Since hot carcass weight (HCW) and backfat are associated with animal age in Uruguayan beef carcasses, the study also looked at two HCW and two backfat thickness within age category to determine the relationship between these traits and meat quality. Carcasses in the 0-2 teeth category were further segregated into HCW (< and ≥ 225 kg) and backfat (< and ≥ 5 mm) categories. For 4 teeth and 6-8 teeth carcasses the categories were, HCW < and ≥ 240 kg and backfat < and ≥ 5mm and HCW < and ≥ 265 kg and backfat < and ≥ 7 mm, respectively. Carcasses were segregated into appropriate fat thickness categories based on carcass backfat measured at the 11^{th} rib surface. Data from two official classification systems were collected, the American (USDA, 1997) and the Uruguayan (INAC, 1997). The Uruguayan system data was collected on hot carcasses (1 h postmortem), while the USDA data was collected on cold carcasses 18-24 h postmortem. Colorado State University personnel collected data for preliminary yield grade, percentage kidney, pelvic, and heart fat, lean maturity, skeletal maturity, overall maturity, marbling score and quality grade. The following carcass data were collected after ribbing the left side of the carcass at the 11^{th} rib cut surface of the *longissimus dorsi*: actual backfat, ribeye area (output from a cold computer vision system, CVS, Research Management System, USA), lean colorimeter measures (L*, a*, b*), and muscle pH and temperature. Lean colorimeter readings were also collected one hour later, following blooming.

An 8-cm portion of the *longissimus dorsi* was removed from the left side of carcasses, labeled, vacuum-packaged and transported to the Meat Science Laboratory at INIA Tacuarembó for shear force analysis after 7 and 14 days of aging at 2 - 4 ^{o}C.

2.1. pH measurements

The pH of the *longissimus dorsi* was determined at three different times: 1, 3 and 18-24 (ultimate) h postmortem. The pH at 1 and 3 h postmortem was measured between the 10 and 11th rib on the left side of the carcasses, at a depth of 2 cm. The measurement of ultimate pH was taken at the 11th rib cut surface in the pistol cut. The muscle pH was measured using a hand-held pH meter (Orion A 230) with a probe type electrode (BC 200, Hanna Instruments), standardized against two pH buffers (4 and 7). The probe was cleaned with alcohol and rinsed with water between uses.

2.2. Temperature determination

The temperature was determined at 1, 3, and 18-24 (ultimate) h postmortem. In the first two measurements, the temperature was taken between the 10 and 11th rib on the left side of the carcasses. The ultimate temperature was collected at the 11th rib cut surface in the pistol cut. In each case, the temperature was determined by a thermometer (Barnant 115) with stainless steel thermocouple (type E).

2.3. Muscle Color determination

Muscle color measurements followed the CIE color convention (CIE, 1986), where the three fundamental outputs are L*, a* and b*. L* is lightness on a scale of 0 (all light absorbed) to 100 (all light reflected); a* spans from + 60 (red) to – 60 (green) and b* spans from + 60 (yellow) to – 60 (blue). Color measurements were made using a Minolta Colorimeter (model C-10) with a 50mm diameter measurement area. They were recorded in triplicate from the exposed *longissimus* muscle between the 10-11th rib immediately following ribbing (cutting between the 10-11th to expose the *longissimus* muscle) surface in the pistol cut (left side). At 1 h post-ribbing, colorimeter readings were collected following the same procedure (L*b, a*b, b*b) to examine the effect of blooming on the three outputs (L*, a*, b*).

2.4. Warner-Bratzler Shear Force determination

The portions of *longissimus dorsi* transported to the Meat Science Laboratory at INIA Tacuarembó were aged for 7 and 14 days at 2-4 ^{o}C. At 7 d postmortem, the cuts were trimmed and sliced to generate 2.54 cm thick steaks. The first steak (at the anterior end) from each *longissimus* was used for shear force determination with 7 d of aging, the second was vacuum-packaged and aged another 7 days for subsequent Warner-Bratzler shear force analysis (WBSF), and the rest of the cut was frozen (-20^{o}C) for further analysis. The steaks aged 7 and 14 days were cooked by immersion within a plastic bag in a water bath (80^{o}C) at an internal temperature of 70^{o}C for 75 min. The internal temperature was monitored using type E thermocouples placed in the approximate geometric center of the steak. Six cores (1.27 cm in diameter) were removed parallel to the muscle fiber orientation from each steak. A single peak WBSF measurement was obtained for each core using a WBSF machine (G-R Electric Manufacturing Co, Manhattan, KS). Individual-core peak shear force values were averaged to assign a mean peak WBSF value to each steak.

2.5. Statistical analysis

Descriptive statistics were computed in this experiment for selected carcass traits, pH, temperature, colorimeter readings and WBSF values. A Shapiro-Wilk test ($P<0.01$) from Univariate procedure (SAS, 1990) was run to study whether these variables had a normal distribution.

The model used in this experiment was

$$Y_{ijkl} = \mu + A_i + B_j + C_k + ABC_{ijk} + E_{ijkl}$$

where

Y_{ijkl} = ijklth Warner-Bratzler shear force at 7 and 14 days of aging,

μ = overall mean,

A_i = effect of the ith dentition,

B_j = effect of the jth hot carcass weight,

C_k = effect of the kth fat thickness

ABC_{ijk} = interaction effect of ijkth dentition * hot carcass weight*fat thickness,

E_{ijkl} = residual error

Least squares means were calculated and separated using the PDIFF procedure (SAS, 1990). To better understand the relationship between the independent and dependent (WBSF values) variables correlation analysis and multiple regression analysis using the stepwise procedure (SAS, 1990). Objective muscle color measurements and muscle pH values were plotted against mean shear force values, and coefficients of determination (R^2) between these variables were obtained with the mentioned procedures. Contingency tables were analyzed to determine the efficacy of carcasses sorting by tenderness using the best model.

3. Results and Discussion

3.1 Carcass traits.

In this study, significant differences (P>0.05) in WBSF 7 and WBSF 14 across dentition, HCW and backfat were not detected. The WBSF mean obtained for 7 and 14 days of aging were 4.06 kg (CV: 35.33%) and 3.42 kg (CV: 30.65%). These values for WBSF would be considered acceptable from a consumer satisfaction viewpoint (Shackelford et al., 1991; Miller et al., 2001); but it is not the purpose of this study to compare these data with other reports because differences in breeds, chilling process and cooking methods could affect the results. The statistical analysis for the mentioned model showed that no variable was significant (P>0.05) for WBSF at 7 and 14 days. These results agree with Lawrence et al (2001) and Wyhtes and Shorthose (1991) who did not find significant differences in WBSF and sensory panel tenderness among the five dental classes. These authors supported the concept that classification of carcasses based on dentition should not be used in place of USDA carcass maturity to segregate carcasses for *longissimus* steak tenderness. Means and standard deviation for all measured variables and for all, 0-2 teeth, 4 teeth and 6-8 teeth carcasses are presented in Table 4.2. The range in QG variables, marbling and overall maturity scores, was wide, going from Traces to Slightly Abundant and A to E, respectively, but the carcasses were concentrated in Traces (35.06%) and Slight (55.17%) levels of marbling and in A (76.44%) overall maturity category. QG scores varied from Utility to Choice, where 88.5% of the carcasses were classified as Standard (44.25%) and Select (44.25%) (Table 4.3).

In comparing the carcasses by dentition, significant differences were found between the 6-8 teeth group and the other two groups in skeletal maturity ($P<0.01$) and between 6-8 teeth and 0-2 teeth in lean maturity ($P<0.05$). This last difference also was confirmed with L* values ($P<0.01$) (Table 4.4). Grouping by backfat (≤ 6 mm and > 6 mm), differences in lean maturity, marbling and QG ($P<0.01$) were observed in this study.

As expected, the pH values (pH_1, pH_3 and pH_u) were lowest ($P<0.05$) and temperatures were highest (T_1, $P<0.01$, and T_3, $P<0.05$) for the fattest group (Table 4.4). The positive relationship between muscle temperature and subcutaneous fat thickness is a result of the insulation effect of fat. Bowling et al (1977) reported that the insulating effects of moderate levels of subcutaneous fat reduce the rate of carcass temperature decline and accelerate glycolysis during post-mortem chilling. This result is in agreement with Laurent et al. (1991) who found that fat removed sides showed lower temperatures and higher pH at 1 h post-mortem than sides without trimming.

This study also focused on the differences in weight and finishing within each age group. In Table 4.5, means and standard deviations of all variables in 0-2 teeth carcass group are presented. There were significant differences in WBSF 7 between groups, with the toughest ($P<0.05$) steaks coming from light and lean carcasses. The carcasses with HCW ≥ 225 and Fat < 5 mm, had the most tender steaks but the number of observations is small (n=4). Lean maturity was associated with fat level ($r= -0.39$, $P<0.05$), as the fattest carcasses were less mature ($P<0.05$) than the leanest ones. The b* values had a response similarly to lean maturity across fat groups ($r= 0.46$, $P<0.01$). T_1 and T_3 were higher in the fat groups (≥ 5mm) with the exception of the group with low observations. Heavy and fat carcasses were different in T_1 ($P<0.05$) and T_3 ($P<0.01$) from light and lean ones. For 4-teeth carcasses (Table 4.6), no differences in WBSF 7 and WBSF 14 were detected among groups. Again the fattest groups had the lowest lean maturity levels and the highest lean maturity was found in the group with HCW>240 kg and backfat<5mm. This group also showed the lowest values of L* and a*. The coefficient of correlation between lean maturity and L* and a* was –0.67 and –0.54, respectively ($P<0.01$). Page et al. (2001) and Wulf and Wise (1999) also reported that lean maturity was more highly correlated with L* than with a* or b*. MARB was moderately correlated with backfat ($r=0.46$,

P<0.01). The groups with fat ≥ 5mm were higher in degree of MARB and higher in QG scores than the leanest groups. MARB and QG had a r=0.54 (P<0.01). T_1 and T_3 were different (P<0.01) between the extreme groups. Least square means and standard errors of all studied variables for 6-8 teeth carcasses are presented in Table 4.7. The highest WBSF 7 and WBSF 14 values were observed in the carcass group with HCW>265 kg and backfat<7 mm. MARB, T_1 and T_3 were also higher in the heavy and fat carcass group.

3.2 Correlation Analyses.

Simple correlations of carcass variables and WBSF and color parameters are presented in Table 4.8. YG was the variable most highly correlated (P<0.01) with both WBSF 7 and WBSF 14. This could be explained by subcutaneous fat thickness, where higher levels of fat would be associated with lower WBSF values. In a similar study with female carcasses, a* muscle color was negatively correlated (P<0.05) with WBSF 7 and WBSF 14. This correlation was higher for female carcasses (r=-0.57, P<0.01, for both aging times) than for male carcasses (r= -0.47 and -0.40, for WBSF at 7 and 14 days respectively). All correlation coefficients between muscle color and WBSF were negative. Similar findings have been reported by Wulf et al. (1997), Wulf and Page (2000) and Vote et al. (2003), showing that dark color muscles could be associated with tough steaks. Vote et al. (2003) had reported moderate correlations between lean a* and WBSF in two experiments (r= - 0.38 and -0.40, P<0.05). In this study, lean maturity was lowly correlated with WBSF 7 and WBSF 14 (r=0.14 and 0.17, respectively). For the female carcass experiment, the correlation (P<0.01) between lean maturity and WBSF 7 and WBSF 14 was r= 0.38 and 0.47, respectively**.** Studying the relationship of color parameters with some of the measured variables, lean L*, a* and b* were moderately correlated (P<0.01) with pH_u, with a* having the highest correlation (r=-0.44). This was also observed in the aforementioned female carcass research, where the correlation coefficient between lean a* and pH_u was -0.47 (P<0.01). Ledward et al. (1992) reported that the negative correlations between colorimeter readings and pH_u could be explained by the oxygenation of the myoglobin and the reflectance of the light. At higher pH_u meat will be darker in color because less

water is free to reflect the light and less oxygenation of the surface myoglobin occurs. Page et al. (2001) also reported that muscle pH affected muscle color, altering hue more than lightness. Lean L* was most closely related with lean maturity (r=-0.61, P<0.01). This result is concordant with the data reported by Vote et al. (2003) who found correlations between L* and lean maturity in the range of -0.52 and -0.69 in different experiments using the CVS BeefCam color output. Page et al. (2001) reported simple correlations of -0.58, -0.31 and -0.43 between lean maturity and L*, a* and b* muscle color, respectively. These correlations are similar to the results in this study suggesting the importance of lean a* as indicator of meat quality and especially, of tenderness in these studies.

3.3 Relationship between pH_3 and WBSF and color.

When pH_3 was used to segregate carcasses into low ($pH_3 < 5.8$), intermediate (5.8-6.2) and high pH (>6.2) groups, no differences (P>0.05) were observed in WBSF 7 and WBSF 14, across the three categories of age (Table 4.9). These results are not in agreement with the concept that for optimum tenderness it is necessary to produce an intermediate rate of glycolysis (Pike et al., 1993). Jones and Tatum (1994), however, reported that carcasses with a pH_3 lower than 5.8 produced steaks with the highest tenderness ratings.

There was a difference (P<0.01) in color (L*, a* and b*) among the three pH_3 groups for all carcasses and 4-teeth carcasses. For 0-2 and 6-8 teeth carcasses, there were differences (P<0.01) between the groups with $pH_3 \leq 6.2$ and the group with $pH_3 > 6.2$ in all three color measurements. The darkest color in the high pH_3 group is explained by the high proportion of the carcasses in this group that were classified as dry, firm and dark (DFD).

3.4. Relationship between pH_u and WBSF and color measurements.

The observed response between WBSF and pH_u was somewhat curvilinear (Figure 4.1). The coefficient of determination (R^2) for WBSF 7 and WBSF 14 were 0.13 and 0.09, respectively, in a 2^{nd} order-polynomial equation. Transforming the WBSF values (1/WBSF) increased the R^2 to 0.22 and 0.15 for WBSF 7 and WBSF 14, respectively. A similar response in beef had been reported by Purchas, (1990), Jeremiah et al. (1991), and Purchas et al. (1999).

Means and standard error for WBSF 7 and WBSF 14 across three pH_u groups (low: <5.8, intermediate: 5.8-6.2 and high: >6.2) are presented in Table 4.11. The intermediate pH_u group had the highest WBSF for 7 and 14 days of aging. This pH_u group was different in tenderness from the others two pH_u groups when all carcasses ($P<0.01$) and 0-2 teeth carcasses ($P<0.05$) were included in the analysis. For 4-teeth carcasses, a significant difference ($P<0.01$) was only observed between the intermediate and high pH_u groups. In almost all age groups, the WBSF values in high pH_u group were the lowest (except in the 6-8 teeth carcasses). Jeremiah (1991), Lawrie (1992), Dransfield (1994), and Silva et al. (1999) reported increases in tenderness associated with high pH_u in beef. Watanabe et al. (1996) and Beltrán et al. (1997) reported a higher rate of tenderization in DFD cuts. A possible explanation may be that there is greater fragmentation of myofibrils and lower cooking losses (higher water holding capacity) in DFD than normal meat.

This relationship was confirmed by the color measurements (L*, a* and b*) for each pH_u group (Table 4.12). The high pH_u carcass group had the darkest color (lowest values of L*, a* and b*) and its L*, a* and b* values were different ($P<0.01$) from the other pH_u groups (intermediate and low). This trend was observed in all age groups. The intermediate pH_u group was also different ($P<0.01$) in colorimeter readings from the low pH_u group.

From the correlation analyses and the relationship among pH_u, color and WBSF, lean a* appears to be more closely related to tenderness that other quality variables. Consistent with the median and the mean obtained in this study, a threshold of 20 in lean a* values was used to separate carcasses by tenderness. The carcasses with a* colorimeter readings ≥ 20 had lower ($P<0.01$) WBSF 7 and WBSF 14 values than the group of carcasses with lean a* values < 20 (Table 4.13). These results were obtained when all carcasses were considered and when only the carcasses with $pH_u < 5.8$ were analyzed.

To better understand the relationship among these variables, a comparison among pH_u and lean a* means for different levels of WBSF at 7 and 14 days of aging (Figure 4.2 and 4.3) was done.

Eliminating the DFD carcass (pH=6.8), no differences (P>0.05) in pH_u were observed among the levels of WBSF 7 and WBSF 14, but there was significant differences in lean a* means tenderness decreased.

3.5 Regression analyses

Multiple linear regression equations were developed to predict WBSF values using USDA quality variables alone and including all the variables considered in this study for all carcasses and the different age groups (0-2, 4, and 6-8 teeth) (Table 4.15 and 4.16). The models were developed using stepwise procedure, with levels of significance (α) of 0.2 required for entering and 0.1 for remaining in the model.

Application of the USDA quality grade factors to Uruguayan steers (Table 4.15) explained in most of the cases 4 to 6 % of the WBSF 7 and WBSF 14 variation, with the exception of WBSF 14 in 6-8 teeth carcass group where lean maturity explained 21% of its variation. The importance of lean maturity was also detected in a study of Uruguayan female carcasses, explaining 15% of the WBSF 7 variation. Vote et al. (2003) reported a partial R^2 for lean maturity of 6 and 8% in the WBSF 14 variation for two different experiments. Marbling showed a low correlation (P>0.05) to WBSF 7 (r=-0.12) and WBSF 14 (r=-0.12) in our study. Wulf et al. (1996), in a study containing mostly carcasses classified as USDA Select, reported no correlation between these variables (P>0.05) and Vote et al. (2003) reported that marbling score did not explain WBSF variation in Select carcasses. In this study almost 90% of the carcasses were classified as Standard and Select and contained Slight and Traces levels of marbling (Table 4.3). These results support earlier findings that the relationship between marbling score and WBSF values depends on the range of marbling evaluated (Smith et al., 1984).

When multiple linear regression procedures were run using all the measurements to predict WBSF values, the main single variable in predicting tenderness for all evaluated carcasses was lean a* (Table 4.15). This colorimeter reading explained by itself 16 to 22% of the WBSF 14 and WBSF 7 variation, respectively. A similar observation was made in female carcasses where lean a* had a

partial R^2 of 0.32 and 0.33 for WBSF 7 and WBSF 14, respectively. Vote et al. (2003) evaluated Choice and Select carcasses and found that lean a* from the CVS BeefCam explained 16% of the WBSF 14 variation. The lean a* parameter was followed by pH_u and T (T_1 or T_3) in the model for all male carcasses (Table 4.15). This was also observed in 0-2 and 4 teeth carcasses. However, for the 6-8 teeth carcass group, REA ($r=-0.55$, $P<0.01$), YG and HCW combined to explain the tenderness variation. REA singularly account for 30% of the WBSF 14 variation. Wyle et al. (2003) and Vote et al. (2003) observed a relationship between this variable and palatability and suggested the possibility of identifying tough steaks using REA from CVS BeefCam adjusted by carcass weight. In this study, QG explained an additional 24% of the WBSF 14 variation in 6-8 teeth carcasses.

According to the variables selected in previous steps and considering development of models to predict tenderness in all carcasses, simple regression equations were calculated. Two models were evaluated using lean a*, pH_u and T_3, and the adjusted R^2 and RMSE (root mean square error) are presented in Table 4.17 for all carcasses and carcasses with $pH_u < 5.8$. These models performed poorly in the 6-8 teeth carcass group, where other variables (REA, QG, and HCW) were more related to WBSF variation. In the 4 teeth carcass group, T_3 contributed to account for additional 6 to 7% and 11 to 14% of the observed variation in WBSF 7 and WBSF 14, respectively.

3.6 Contingency tables

The relationship between real WBSF 7 and 14 and predicted WBSF 7 and 14 are presented in Fig. 4.4 and 4.5. The regression equations developed to calculate the predicted WBSF values were

$$\text{WBSF 7} = -105.27 - 0.214 * (\text{lean a*}) + 39.797 * (pH_u) - 3.477 * (pH_u)^2$$

$$\text{WBSF 14} = -59.21 - 0.129 * (\text{lean a*}) + 22.888 * (pH_u) - 2.004 * (pH_u)^2$$

The efficacy of these models to predict carcass tenderness was studied by a traditional two-way contingency table, in which an arbitrary WBSF threshold at evaluation is selected for a decision point. The estimate of the accuracy is based on a true positive fraction (TP: tender) or animals correctly predicted to be tender plus a true negative fraction (TN: tough) or animals correctly predicted to be tough. Sensitivity and specificity represent two kinds of accuracy, the first for actually positive cases and the second for actually negative cases. Both are expressed as a percentage. The

contingency tables were constructed using two WBSF thresholds according to the literature, using 4.5 and 3.4 kg WBSF values. Shackelford et al. (1991) published the first threshold relating WBSF values to consumer data and reported that the transition between tough and tender occurred at 4.5 kg. This was confirmed later by Miller et al (2001) who found an average transition of 4.6 kg. These authors studying the consumer acceptability for beefsteak tenderness also obtained 99% consumer satisfaction with a value of 3.4 kg.

Four combinations (Table 4.18 and 4.19) were analyzed using two WBSF thresholds and two aging periods. The accuracy for both aging periods was better when 4.5 kg was considered as the threshold. With a threshold of 3.4 kg, the accuracy of the models was moderate (61 and 66 % for WBSF 14 and WBSF 7, respectively). Here, in both aging periods, specificity (72 and 89% for 14 and 7 days of aging, respectively) was higher than sensitivity, showing that the model was better at identifying tough steaks than tender ones.

4. Implications

This study attempted to give to the Uruguayan meat chain components a primary knowledge about selected male beef carcasses in terms of muscle pH, temperature, color and carcass traits. The population of cattle in this study was selected to be representative of steers slaughtered in Uruguay, stratified by age. For these animals, objective measures of muscle color, specifically lean a*, was effective in predicting WBSF. This variable explained 22 and 16% of WBSF 7 and WBSF 14 variation, by itself. However, the prediction of WBSF in 6-8 teeth carcasses was better using other variables such as pH_3 and REA. The addition of the USDA QG standards to the Uruguayan male carcasses grading did not contribute to improving the effectiveness of sorting carcasses into tenderness groups, with the exception of WBSF 14 prediction in 6-8 teeth carcasses. Based on these findings and the ability to apply them in a practical manner in the Uruguayan meat industry, it appears ultimate pH and lean a* measured at ribbing might be useful in sorting beef carcasses likely to yield tough or tender steaks depending on the defined WBSF threshold. Further research should be conducted to better understand the relationship between pH/color and tenderness and how to ensure adequate levels of tenderness.

Literature Cited

Beltrán, J.A., I. Jaime, P. Santolaria, C. Sañudo, P. Albertí, and P. Roncalés. 1997. Effect of stress-induced high post-mortem pH on protease activity and tenderness beef. Meat Sci. 45(2):201-207.

Boleman, S.J., S.L. Boleman, R.K. Miller, J.F. Taylor, H.R. Cross, T.L. Wheeler, M. Koohmaraie, S.D. Shackelford, M.F. Miller, R.L. West, and J.W. Savell. 1997. Consumer Evaluation of beef of known categories of tenderness. J. Anim. Sci. 75:1521-1524.

Bowling, R.A., G.C. Smith, T.R. Dutson, Z.L. Carpenter, and W.M. Oliver. 1977. Comparison of beef finished on forage versus grain. J. Anim. Sci. 45:209-215.

C.I.E., 1986. Colorimetry (2nd ed.) Commission International de l'Éclairage, Publication CIE 15.2. Vienna: CIE.

Dransfield, E. 1994. Tenderness of meat, poultry and fish. In A.M. Pearson and T.R. Dutson (Eds), *Quality attributes and their measurement in meat, poultry and fish products.* Advances in meat research series vol. 9 (pp. 289-315). London: Blackie Academic and Professional.

George, M.H., J.D. Tatum, K.E. Belk, and G.C. Smith. 1999. An audit of retail beef loin steak tenderness conducted in eight U.S. cities. J. Anim. Sci. 77: 1735-1741.

I.N.A.C. (1997). Sistema oficial (uruguayo) de clasificación y tipificación de carne vacuna. Resolución 65/97. Montevideo, Uruguay.

Jeremiah, L.E., A.K. Tong, and L.L. Gibson. 1991. The usefulness of muscle color and pH for segregating beef carcasses into tenderness groups. Meat Sci. 30: 97-114.

Jones, B.K. and J.D. Tatum. 1994. Predictors of beef tenderness among carcasses produced under commercial conditions. J. Anim. Sci. 72:1492-1501.

Laurent, K.M.,M.M. Pike, T.D. Bidner, A.M. Saxton, and A.M. McMillin. 1991. Effect of subcutaneous fat removal and aging on beef tenderness. J. Anim. Sci. 69(Suppl.2):19.

Lawrence, J.D. 2002. Quality assurance down under: market access and product differentitation. http: www.card.iastate.edu/matric/publications.html.

Lawrence, T.E., J.D. Whatley, T.H. Montgomery, L.J. Perino, and M.E. Dikeman. 2001. Influence of dental carcass maturity classification on carcass traits and tenderness of *longissimus* steaks from commercially fed cattle. J. Anim. Sci. 79:2092-2096.

Lawrie, R. 1992. *The chemistry of muscle based foods*. Eds. E.Ledward, D. Johnston, and M. Knight. (pp 43-46). Royal Society of Chemistry, Cambridge, UK.

Ledward, D.A. 1992. Color of the raw and cooked meat. In D.E. Johnston, M. Knight, and D.A. Ledward. *The chemistry of muscle based foods*. Cambridge, UK:Royal Society of Chemistry .pp:128-144.

Lochner, J.V., R.G. Kauffman, and B.B. Marsh. 1980. Early post-mortem cooling rate and beef tenderness. Meat Sci. 4:227-241.

Miller, M.F., M.A. Carr, C.B. Ramsey, K.L. Crockett, and L.C. Hoover. 2001. Consumer thresholds for establishing the value of beef tenderness. J. Anim.Sci. 79:3062-3068.

Page, J.K., D.M. Wulf, and T.R. Schwotzer. 2001. A survey of beef muscle color and pH. J. Anim. Sci. 79:678-687.

Pike, M.M., T.P. Ringkob, D.D. Beekman, Y.O. Koh, and W.T. Gerthoffer. 1993. Quadratic relationship between early post-mortem glycolytic rate and beef tenderness. Meat Sci. 34:13-26.

Purchas, R.W. 1990. An assessment of the role of pH differences in determining the relative tenderness of meat from bulls and steers. Meat Sci. 27:129-140.

Purchas, R. W., X. Yan, and D.G. Hartley. 1999. The influence of a period of aging on the relationship between ultimate pH and shear values of beef *m. longissimus thoracis.* Meat Sci. 51:135-141.

Shackelford, S.D, M. Koohmaraie, G. Whipple, T.L. Wheeler, M.F. Miller, J.D. Crouse, and J.O. Reagan. 1991. Predictors of beef tenderness: Development and verification. J. Food Sci. 56(5):1130-1135.

Silva, J.A., L. Patarata, and C. Martins. 1999. Influence of ultimate pH on bovine meat tenderness during aging. Meat Sci. 52:453-459.

Smith, G.C., Z.L. Carpenter, H.R. Cross, C.E. Murphey, H.C. Abrahan, J.W. Savell, G.W. Davis, B.W. Berry, and F.C. Parrish Jr. 1984. Relationship of USDA marbling groups to palatability of cooked beef. J. Food Qual. 7:289-308.

Thompson, J. 2002. Managing meat tenderness. Meat Sci. 62:295-308.

USDA. 1997. Official United States standards for grades of carcass beef. Agric. Marketing Serv., USDA, Washington, DC.

Vote, D.J., K.E. Belk, J.D. Tatum, J.A. Scanga, and G.C. Smith. 2003. Online prediction of beef tenderness using a computer vision system equipped with a BeefCam module. J. Anim. Sci. 81:457-465.

Watanabe, A., C.C. Daly, and C.E. Devine. 1996. The effects of the ultimate pH of meat on tenderness changes during aging. Meat Sci. 42(1):67-78.

Wulf, D.M., J.B. Morgan, J.D. Tatum, and G.C. Smith. 1996. Effects of animal age, marbling score, calpastatin activity, subprimal cut, calcium injection, and degree of doneness on the palatability of steaks from Limousin steers. J. Anim. Sci. 74: 569-576.

Wulf, D.M., S.F. O'Connor, J. D. Tatum, and G. C. Smith. 1997. Using objective measures of muscle color to predict beef *longissimus* tenderness. J. Anim. Sci. 75:684-692.

Wulf, D.M., and J.W. Wise. 1999. Measuring muscle color on beef carcasses using the L* a* b* color space. J. Anim. Sci. 77:2418-2427.

Wulf, D.M. and J.K. Page. 2000. Using measurements of muscle color, pH, and electrical impedance to augment the current USDA beef quality grading standards and improve the accuracy and precision of sorting carcasses into palatability groups. J. Anim. Sci. 78:2595-2607.

Wulf, D.M., R.S. Emnett, J.M. Leheska, and S.J. Moeller. 2002. Relationships among glycolytic potential, dark cutting (dark, firm, and dry) beef, and cooked beef palatability. J. Anim. Sci. 80:1895-1903.

Wyle, A.M., D.J. Vote, D.L. Roeber, R.C. Cannell, K.E. Belk, J.A. Scanga, M. Goldberg, J.D. Tatum, and G.C. Smith. 2003. Effectiveness of the SmartMV prototype BeefCam system to sort beef carcasses into expected palatability groups. J.Anim.Sci. 81:441-448.

Wythes, J.R., and W.R. Shorthose. 1991. Chronological age and dentition effects on carcass and meat quality of cattle in northern Australia. Aust. J. Exp. Agric. 31:145-152.

Table 4.1 Definition of variables

Variables	Definition
Con	INAC Conformation 1=I (best conf.) to 6=R (worst conf.)
Fin	INAC Finishing 0=low fat to 3=high fat
Dentition	Dentition 0, 2, 4, 6, 8 teeth
HCW	Hot carcass weight (kg)
Fat	Subcutaneous fat between 10-11th rib (mm)
YG	USDA Yield grade (1 to 5)
Lean mat.	Lean maturity 0=A^{00}, 100=B^{00}, 200=C^{00} , 300=D^{00} , 400=E^{00}
Skeletal mat.	Skeletal maturity 0=A^{00}, 100=B^{00}, 200=C^{00} , 300=D^{00} , 400=E^{00}
Overall mat.	Overall maturity 0=A^{00}, 100=B^{00}, 200=C^{00} , 300=D^{00} , 400=E^{00}
MARB	Marbling score 100=Practically devoid^{00}, 200=Traces^{00}, 300=Slight^{00}, 400=Small^{00}, 500= Modest^{00}, 600=Moderate^{00}, 700=Sl.abundant^{00}, 800=Mod. Abundant^{00}
QG	USDA Quality grade 200=Cutter^{00}, 300=Utility^{00}, 400=Commercial^{00}, 500=Standard^{00}, 600=Select^{00},700=Choice^{00}, 800=Prime^{00}
Rea	Rib eye area (cm^2)
pH_1 pH_3 pH_u	pH at 1, 3, 18-24 h postmortem
T_1 T_3 T_u	Temperature at 1, 3, 18-24 h postmortem (^{o}C)
L*	Luminance 0=black to 100= white
a*	+60= red to –60=green
b*	+60= yellow to –60=blue
Lb* ab* bb*	L*, a*, b* with 1 h of blooming time after ribbing
WBSF 7	Warner-Bratzler shear force with 7 days of aging (kg)
WBSF 14	Warner-Bratzler shear force with 14 days of aging (kg)

Table 4.2 Mean and standard deviation of main variables in all, 0-2 teeth, 4 teeth and 6-8 teeth male carcasses.

	All carcasses		0-2 t. carcasses		4 t. carcasses		6-8 t. carcasses	
Variables	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
Con	3.13	0.44	3.03	0.49	3.16	0.40	3.16	0.47
Fin	1.76	0.47	1.76	0.43	1.72	0.50	1.82	0.44
Dentition	4.50	2.16	1.74	0.68			7.51	0.87
HCW	243.47	36.30	229.28	28.81	239.44	33.65	261.63	39.45
Fat	6.04	3.53	5.50	3.60	5.41	3.26	7.57	3.55
YG	2.77	0.46	2.65	0.38	2.69	0.39	3.03	0.57
Lean mat.	117.46	78.01	92.29	61.25	120.54	77.07	133.08	87.63
Sk. mat.	70.92	43.47	62.11	31.89	64.48	22.30	89.18	68.25
Ov. mat.	84.94	49.02	73.42	40.15	79.66	36.17	103.27	67.65
MARB	326.55	67.21	312.89	72.78	320.00	56.89	348.78	75.29
QG	539.08	79.53	534.21	81.46	539.08	61.67	542.86	104.08
Rea	52.21	8.31	54.40	9.44	51.40	7.92	51.98	7.91
pH_1	6.15	0.28	6.11	0.27	6.12	0.27	6.22	0.28
pH_3	5.94	0.29	5.89	0.26	5.93	0.30	6.00	0.27
pH_u	5.74	0.34	5.71	0.29	5.78	0.37	5.71	0.34
T_1	33.65	2.72	33.40	2.67	33.68	2.63	33.81	2.94
T_3	21.65	3.90	21.52	3.09	21.34	3.21	22.31	5.33
T_u	2.85	0.79	2.91	0.85	2.80	0.69	2.89	0.90
L*	30.37	3.26	32.53	3.58	29.94	3.20	29.61	2.48
a*	19.23	3.66	19.56	2.97	18.45	3.80	20.34	3.57
b*	8.63	2.82	9.44	2.33	7.99	2.42	9.16	3.47
Lb*	31.26	3.34	33.23	3.67	30.83	3.21	30.49	2.69
ab*	21.71	4.04	22.11	3.46	21.08	4.27	22.54	3.91
bb*	10.31	2.51	11.27	2.63	9.94	2.53	10.27	2.24
WBSF7	4.06	1.46	3.98	1.56	4.25	1.59	3.76	1.02
WBSF14	3.42	1.04	3.43	1.19	3.52	1.10	3.25	0.76

Table 4.3 Carcass frequencies for each USDA quality factor (overall maturity, marbling and quality grade)

Ov. Mat	Perc. (%)	Marbling	Perc. (%)	Quality grade	Perc. (%)
A	76.44	**Traces**	35.06	**Utility**	4.02
B	18.97	**Slight**	55.17	**Commercial**	0.57
C	4.02	**Small**	6.90	**Standard**	44.25
D	-	**Modest**	1.15	**Select**	44.25
E	0.57	**Moderate**	1.72	**Choice**	6.90

Table 4.4 Least square means and standard errors ( ) for quality variables among age groups (0-2 teeth: n= 38, 4 teeth: n= 87, and 6-8 teeth: n= 49)

Variables	0-2 teeth	4 teeth	6-8 teeth
Lean mat.	86.08[b]	113.81[ab]	131.79[a]
	(13.75)	(10.44)	(13.20)
Skeletal mat.	61.20[c]	63.53[c]	88.27
	(7.05)	(4.75)	(6.50)
Overall mat.	70.72[c]	76.90[c]	101.4[a]
	(7.94)	(5.35)	(7.31)
MARB	318.84	324.76	344.07
	(10.68)	(7.19)	(9.82)
QG	542.75	548.00	544.81
	(12.67)	(8.54)	(11.66)
pH_1	6.06	6.10	6.15
	(0.05)	(0.03)	(0.06)
pH_3	5.82	5.91	5.95
	(0.05)	(0.03)	(0.06)
pH_u	5.64	5.74	5.71
	(0.07)	(0.04)	(0.08)
T_1	33.96	33.83	33.82
	(0.49)	(0.29)	(0.58)
T_3	22.11	22.61	21.37
	(0.74)	(0.43)	(0.87)
T_u	2.80	2.85	3.10
	(0.16)	(0.09)	(0.18)
L*	32.89[a]	30.09[c]	29.67[c]
	(0.66)	(0.36)	(0.71)
a*	20.27	18.69	20.01
	(0.77)	(0.42)	(0.83)
b*	9.95[a]	8.14[c]	8.95[ab]
	(0.6)	(0.32)	(0.65)
Lb*	33.51[a]	31.02[c]	30.67[bc]
	(0.72)	(0.36)	(0.72)
ab*	23.13	21.46	22.02
	(0.9)	(0.45)	(0.91)
bb*	11.80[a]	10.15[b]	10.25[ab]
	(0.55)	(0.28)	(0.56)
WBSF7	3.79	4.23	3.58
	(0.28)	(0.17)	(0.33)
WBSF14	3.34	3.53	3.29
	(0.21)	(0.12)	(0.24)

[a,b,c] Means in the same row bearing a common superscript letter are not significantly different ($P<0.05$)
Means in the same row with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 4.5 Least square means and standard errors ( ) for quality variables among groups within the same age (0-2 teeth) and with varying in HCW and fat (1:<225 kg<5mm, 2:<225 kg ≥5mm, 3:≥225 kg <5mm and 4: ≥225 kg ≥5mm)

Variables	**1** (n:11)	**2** (n:10)	**3** (n:4)	**4** (n:13)
Lean mat.	143.00[a]	76.67[b]	96.67[ab]	73.33 [b]
	(21.57)	(19.03)	(32.96)	(16.48)
Skeletal mat.	65.45	51.00	60.00	68.46
	(9.77)	(10.25)	(16.21)	(8.99)
Overall mat.	84.54	61.00	72.50	73.85
	(12.32)	(12.92)	(20.43)	(11.33)
MARB	301.82	307.00	370.00	309.23
	(22.00)	(23.08)	(36.49)	(20.24)
QG	518.18	560.00	550.00	523.08
	(24.98)	(26.20)	(41.43)	(22.98)
pH_1	6.16	6.10	6.12	6.06
	(0.08)	(0.09)	(0.14)	(0.08)
pH_3	5.94	5.84	5.99	5.84
	(0.08)	(0.08)	(0.13)	(0.07)
pH_u	5.76	5.71	5.81	5.64
	(0.09)	(0.09)	(0.15)	(0.08)
T_1	31.70 [b]	33.63 [ab]	34.28 [ab]	34.40 [a]
	(0.76)	(0.80)	(1.26)	(0.70)
T_3	19.62[c]	21.80[abc]	20.90 [abc]	23.09 [a]
	(0.86)	(0.91)	(1.44)	(0.80)
T_u	3.09	2.86	2.73	2.86
	(0.28)	(0.28)	(0.44)	(0.24)
L*	31.77	32.47	30.23	34.25
	(1.10)	(1.16)	(1.74)	(1.10)
a*	18.79	19.72	18.32	20.69
	(0.94)	(0.99)	(1.49)	(0.94)
b*	8.54 [b]	9.40 [ab]	8.64 [ab]	10.72[a]
	(0.71)	(0.75)	(1.13)	(0.71)
Lb*	31.72 [b]	33.78 [ab]	31.18 [ab]	34.90 [a]
	(1.11)	(1.17)	(1.75)	(0.97)
ab*	20.04 [b]	23.27 [a]	20.17 [ab]	23.50 [a]
	(1.01)	(1.06)	(1.59)	(0.88)
bb*	9.47 [c]	11.89 [ab]	9.90[bc]	12.65 [a]
	(0.74)	(0.78)	(1.17)	(0.65)
WBSF7	4.99 [a]	3.70[ab]	3.17 [b]	3.61 [b]
	(0.44)	(0.47)	(0.74)	(0.41)
WBSF14	4.08	3.21	3.11	3.13
	(0.35)	(0.37)	(0.58)	(0.32)

[a,b,c] Means in the same row bearing a common superscript letter are not significantly different (P<0.05)
Means in the same row with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 4.6 Least square means and standard errors ( ) for quality variables among groups within the same age (4 teeth) and with varying in HCW and fat (1: ≤240 kg <5mm, 2: ≤240 kg ≥5mm, 3: >240 kg <5mm and 4: >240 kg ≥5mm)

Variables	**1** (n:23)	**2** (n:28)	**3** (n:17)	**4** (n:19)
Lean mat.	124.71^{ab}	99.47^{b}	167.78^{a}	111.82^{ab}
	(18.33)	(17.34)	(25.19)	(22.79)
Skeletal mat.	60.00	63.57	72.35	64.21
	(4.65)	(4.21)	(5.40)	(5.11)
Overall mat.	80.43	72.86	93.53	76.32
	(7.51)	(6.81)	(8.74)	(8.26)
MARB	295.22^{b}	329.64^{a}	317.06^{ab}	338.42^{a}
	(11.56)	(10.48)	(13.44)	(12.72)
QG	534.78^{ab}	553.57^{a}	505.88^{b}	552.63^{a}
	(12.51)	(11.34)	(14.55)	(13.76)
pH_1	6.10	6.05	6.22	6.18
	(0.06)	(0.05)	(0.07)	(0.06)
pH_3	5.86	5.88	6.06	5.98
	(0.06)	(0.06)	(0.08)	(0.07)
pH_u	5.73	5.71	5.90	5.81
	(0.08)	(0.07)	(0.09)	(0.08)
T_1	32.43^{c}	33.60^{abc}	34.07^{abc}	35.07^{a}
	(0.52)	(0.47)	(0.65)	(0.59)
T_3	19.97^{c}	21.36^{abc}	21.77^{abc}	22.68^{a}
	(0.65)	(0.59)	(0.80)	(0.73)
T_u	2.89	2.91	2.52	2.79
	(0.15)	(0.13)	(0.18)	(0.16)
L*	30.82^{a}	30.60^{a}	28.47^{b}	29.15^{ab}
	(0.68)	(0.59)	(0.80)	(0.73)
a*	18.66^{ab}	19.18^{a}	16.71^{b}	18.53^{ab}
	(0.82)	(0.71)	(0.97)	(0.89)
b*	8.19	8.49	7.01	7.80
	(0.53)	(0.46)	(0.62)	(0.57)
Lb*	31.60^{a}	31.60^{a}	29.28^{b}	30.16^{ab}
	(0.65)	(0.59)	(0.76)	(0.72)
ab*	21.01^{abc}	22.64^{a}	19.01^{c}	20.72^{abc}
	(0.86)	(0.78)	(1.01)	(0.95)
bb*	10.22^{ab}	10.83^{a}	8.65^{c}	9.45^{abc}
	(0.51)	(0.46)	(0.59)	(0.56)
WBSF7	4.12	3.83	4.61	4.73
	(0.33)	(0.30)	(0.38)	(0.36)
WBSF14	3.43	3.38	3.73	3.65
	(0.23)	(0.21)	(0.27)	(0.26)

^{a,b,c} Means in the same row bearing a common superscript letter are not significantly different ($P<0.05$)
Means in the same row with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 4.7 Least square means and standard errors ( ) for quality variables among groups within the same age (6-8 teeth: 49) and with varying in HCW and fat (1: ≤265kg <7mm , 2: ≤265 kg ≥7mm, 3:>265 kg <7mm and 4: >265 kg ≥7mm)

Variables	**1** (n:9)	**2** (n:16)	**3** (n:12)	**4** (n:12)
Lean mat.	153.33	110.77	158.00	125.00
	(36.25)	(24.63)	(28.08)	(28.08)
Skeletal mat.	87.78	90.00	90.83	87.50
	(23.50)	(17.62)	(20.34)	(20.34)
Overall mat.	103.33	93.75	112.50	106.67
	(23.15)	(17.36)	(20.05)	(20.05)
MARB	312.22 [c]	341.25 [c]	320.00[c]	415.00[a]
	(22.03)	(16.53)	(19.08)	(19.08)
QG	500.00	568.75	508.33	575.00
	(33.92)	(25.44)	(29.37)	(29.37)
pH_1	6.23 [ab]	6.08[b]	6.30 [a]	6.31 [a]
	(0.09)	(0.07)	(0.08)	(0.08)
pH_3	6.03	5.90	6.10	6.03
	(0.09)	(0.07)	(0.08)	(0.08)
pH_u	5.86	5.68	5.69	5.67
	(0.11)	(0.09)	(0.10)	(0.10)
T_1	31.46 [c]	33.54 [c]	33.32 [c]	36.39 [a]
	(0.83)	(0.64)	(0.72)	(0.72)
T_3	19.63 [b]	22.17 [ab]	21.57 [ab]	25.24 [a]
	(1.71)	(1.33)	(1.48)	(1.48)
T_u	2.79	2.82	2.94	3.02
	(0.31)	(0.24)	(0.27)	(0.27)
L*	28.69	30.23	29.38	29.75
	(0.83)	(0.65)	(0.72)	(0.72)
a*	19.24	20.56	19.52	21.72
	(1.19)	(0.92)	(1.03)	(1.03)
b*	8.21	8.93	9.98	9.33
	(1.18)	(0.91)	(1.02)	(1.02)
Lb*	29.68	31.18	30.21	30.45
	(0.91)	(0.68)	(0.82)	(0.79)
ab*	21.54	22.69	22.59	23.06
	(1.34)	(1.00)	(1.21)	(1.16)
bb*	9.80	10.60	10.10	10.34
	(0.77)	(0.57)	(0.69)	(0.66)
WBSF7	3.27 [c]	3.60 [bc]	4.52 [a]	3.59[bc]
	(0.31)	(0.24)	(0.27)	(0.27)
WBSF14	3.07 [ab]	3.07 [b]	3.69 [a]	3.20[ab]
	(0.25)	(0.18)	(0.21)	(0.21)

[a,b,c] Means in the same row bearing a common superscript letter are not significantly different ($P<0.05$)
Means in the same row with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 4.8 Main simple correlations between carcass variables and tenderness and color for all male carcasses

Variables	WBSF7	WBSF14	Variables	L*	a*	b*
YG	- 0.22**	- 0.22**	**Dentition**	- 0.44**	0.23*	0.01
Lean mat.	0.14	0.17*	**Lean mat.**	- 0.61**	- 0.43**	- 0.32**
MARB	- 0.12	- 0.12	**QG**	0.19*	0.37**	0.17
QG	- 0.13	- 0.15	**pH_1**	- 0.32**	- 0.25**	- 0.17
L*	-0.19*	-0.20*	**pH_3**	- 0.32**	- 0.22**	- 0.16
a*	- 0.47**	- 0.40**	**pH_u**	- 0.20*	- 0.44**	- 0.32**
b*	- 0.29**	- 0.25**				

** Significative at 1%
* Significative at 5%

Table 4.9 WBSF least square means and standard errors ( ) for each pH_3 groups considering all and dentition carcass groups

	All males		0-2 teeth		4 teeth		6-8 teeth	
pH_3	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**
< 5.8	3.87	3.34	3.70	3.23	4.06	3.42	3.52	3.22
	(0.20)	(0.14)	(0.43)	(0.32)	(0.28)	(0.20)	(0.33)	(0.24)
5.8-6.2	4.19	3.48	4.27	3.66	4.44	3.57	3.81	3.21
	(0.15)	(0.11)	(0.32)	(0.24)	(0.25)	(0.18)	(0.19)	(0.14)
> 6.2	3.94	3.42	2.56	2.01	4.17	3.62	3.87	3.40
	(0.29)	(0.20)	(1.09)	(0.82)	(0.41)	(0.29)	(0.34)	(0.26)

Means are not significantly different ($P<0.05$)

Table 4.10 Lean L*, a* and b* color least square means for pH_3 groups considering all and dentition carcass groups

	All males			0-2 teeth			4 teeth			6-8 teeth		
pH_3	**L***	**a***	**b***	**L***	**a***	**b***	**L***	**a***	**b***	**L***	**a***	**b***
< 5.8	32.2[a]	21.0[a]	9.7[a]	33.4[a]	20.8[a]	10.3[a]	32.4[a]	20.9[a]	9.7[a]	29.9[a]	21.6[a]	9.1[a]
5.8-6.2	30.6[c]	19.7[b]	8.9[b]	32.7[a]	19.6[a]	9.4[a]	29.6[c]	18.5[c]	7.8[c]	30.4[a]	21.4[a]	10.1[a]
> 6.2	26.4[e]	14.4[d]	5.6[d]	26.2[c]	12.8[c]	5.5[c]	26.3[e]	13.9[d]	5.4[d]	26.5[c]	15.66[c]	6.07[c]

[a,b,c,d,e] Means in the same column bearing a common superscript letter are not significantly different (P<0.05)
Means in the same column with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 4.11 WBSF least square means and standard errors ( ) for pH_u groups considering all and dentition carcass groups

	All males		0-2 teeth		4 teeth		6-8 teeth	
pH_u	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**	**WBSF 7**	**WBSF14**
< 5.8	3.94[c]	3.34 [c]	3.73[b]	3.24 [b]	4.19[abc]	3.49	3.68	3.16
	(0.13)	(0.09)	(0.28)	(0.21)	(0.20)	(0.14)	(0.17)	(0.13)
5.8 – 6.2	4.79[a]	3.87 [a]	5.08 [a]	4.28 [a]	4.97 [a]	3.85	4.13	3.50
	(0.23)	(0.17)	(0.48)	(0.36)	(0.36)	(0.26)	(0.34)	(0.25)
> 6.2	3.38 [c]	3.10 [c]	2.56 [b]	2.01 [b]	3.38[c]	3.16	3.69	3.41
	(0.33)	(0.24)	(1.03)	(0.77)	(0.47)	(0.33)	(0.46)	(0.34)

[a,b,c] Means in the same column bearing a common superscript letter are not significantly different (P<0.05)
Means in the same column with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 4.12 Lean L*, a* and b* color least square means for pH_u groups considering all and dentition carcass groups

	All males			0-2 teeth			4 teeth			6-8 teeth		
pH_u	**L***	**a***	**b***	**L***	**a***	**b***	**L***	**a***	**b***	**L***	**a***	**b***
< 5.8	31.7[a]	21.0[a]	9.7[a]	33.9[a]	20.8[a]	10.4[a]	31.4[a]	20.5[a]	9.1[a]	30.5[a]	21.9[a]	10.1[a]
5.8-6.2	28.8[c]	16.8[c]	7.1[c]	29.6[c]	17.4[c]	7.22[c]	28.7[c]	15.6[c]	6.6[c]	28.4[c]	18.6[c]	7.9[c]
> 6.2	25.1[e]	12.6[e]	4.6[e]	26.2[c]	12.8[e]	5.5[d]	24.9[e]	12.8[e]	4.5[d]	25.1[e]	12.3[e]	4.4[e]

[a,b,c,d,e] Means in the same column bearing a common superscript letter are not significantly different (P<0.05)
Means in the same column with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 4.13 Least square means and standard errors ( ) for the blooming effect (1 h)

	L*	L*bloom	a*	a*bloom	b*	b*bloom
0-2teeth	32.53[a]	33.32 [a]	19.56 [b]	22.11 [a]	9.44 [c]	11.27 [a]
	(3.57)	(3.67)	(2.98)	(3.46)	(2.33)	(2.63)
4 teeth	29.95[a]	30.83[a]	18.45[c]	21.08 [a]	7.99[c]	9.94[a]
	(3.19)	(3.21)	(3.80)	(4.27)	(2.42)	(2.53)
6-8 teeth	29.60[a]	30.49[a]	20.34[b]	22.54[a]	9.15[b]	10.27[a]
	(3.57)	(2.69)	(3.57)	(3.91)	(3.47)	(2.24)

[a,b,c,] Means in the same row bearing a common superscript letter are not significantly different ($P<0.05$) for each variable independently. Means in the same row with one letter of difference differ ($P<0.05$), with more than one letter of difference differ for each variable ($P<0.01$)

Table 4.14 WBSF least square means and standard errors for lean a* color groups using all male carcasses and carcasses with $pH_u < 5.8$

		All carcasses			Carcasses pH<5.8	
a*	**n**	**WBSF 7**	**WBSF14**	**n**	**WBSF 7**	**WBSF14**
< 20	96	4.45[a]	3.62 [a]	54	4.63[a]	3.70[a]
		(0.14)	(0.10)		(0.17)	(0.14)
≥ 20	78	3.57[c]	3.20 [c]	71	3.57 [c]	3.16[c]
		(0.16)	(0.12)		(0.14)	(0.11)

[a,c] Means in the same column with more than one superscript letter of difference differ (P<0.01)

Table 4.15 Multiple regression equations to predict WBSF 7 and WBSF 14 using USDA quality variables for all, 0-2, 4, and 6-8 teeth male carcasses

WBSF 7			WBSF14		
Independent variables	**R^2**	**RMSE**	**Independent variables**	**R^2**	**RMSE**
All carcasses					
Lean maturity	0.03	1.33	Lean maturity	0.04	0.97
Lean maturity, Skeletal maturity	0.06	1.32	Lean maturity, Marbling	0.06	0.96
0-2 teeth carcasses					
No variables met 0.2 significance level for entry into the model for both dependent variables (WBSF7 and WBSF14)					
4 teeth carcasses					
Lean maturity	0.04	1.57	Skeletal maturity	0.04	1.08
6-8 teeth carcasses					
Lean maturity	0.04	0.85	Lean maturity	0.21	0.57

Models were developed using stepwise procedure. R^2= coefficient of determination. RMSE=root mean square error

Table 4.16 Multiple regression equations to predict WBSF 7 and WBSF 14 using yield and quality grades, pH, temperature and color for all, 0-2, 4 and 6-8 teeth male carcasses

WBSF 7			**WBSF14**		
Independent variables	**R^2**	**RMSE**	**Independent variables**	**R^2**	**RMSE**
All carcasses					
a*	0.22	1.60	a*	0.16	0.94
a*, pH_u	0.29	1.50	a*, T_1	0.20	0.90
a*, pH_u, T_3	0.32	1.45	a*, T_1, pH_u	0.24	0.87
			a*, T_1, pH_u, fin	0.26	0.86
0-2 teeth carcasses					
pH_u	0.11	1.32	a*	0.18	1.63
pH_u, con	0.27	1.14	a*, T_3	0.26	1.54
4 teeth carcasses					
a*	0.31	1.88	a*	0.23	1.00
a*, T_3	0.42	1.60	a*, T_1	0.38	0.82
a*, T_3, skeletal mat	0.50	1.43	a*, T_1, skeletal mat	0.43	0.77
a*, T_3, skeletal mat, pH_u	0.53	1.36			
6-8 teeth carcasses					
pH_3	0.17	0.63	Rea	0.30	0.29
pH_3, YG	0.28	0.56	Rea, QG	0.54	0.20
pH_3, YG, Rea	0.34	0.54	Rea, QG, HCW	0.58	0.19
			Rea, QG, HCW, fin	0.62	0.17

Models were developed using stepwise procedure. R^2= coefficient of determination. RMSE=root mean square error

Table 4.17 Simple regression equations to predict WBSF 7 and WBSF 14 using selected variables by stepwise procedure for all, 0-2, 4 and 6-8 teeth carcasses

Dependent variables	**WBSF 7**		**WBSF 14**	
Model 1 = a*, pH_u, pH_u^2				
	adj-R^2	**RMSE**	**adj-R^2**	**RMSE**
All carcasses	0.23	1.31	0.14	0.99
All carcasses pH_u<5.8	0.23	1.19	0.17	0.93
0-2 teeth carcasses	0.17	1.47	0.09	1.20
0-2 t. carcasses pH_u<5.8	0.25	1.22	0.23	1.07
4 teeth carcasses	0.21	1.44	0.13	1.06
4 t. carcasses pH_u<5.8	0.24	1.36	0.20	0.99
6-8 teeth carcasses	0.16	0.94	0.08	0.73
6-8 t. carcasses pH_u<5.8	-0.07	0.92	-0.10	0.69
Model 2 = a*, pH_u, pH_u^2, T_3				
	adj-R^2	**RMSE**	**adj-R^2**	**RMSE**
All carcasses	0.24	1.29	0.15	0.99
All carcasses pH_u<5.8	0.25	1.18	0.18	0.93
0-2 teeth carcasses	0.24	1.41	0.11	1.18
0-2 t. carcasses pH_u<5.8	0.24	1.23	0.20	1.10
4 teeth carcasses	0.28	1.38	0.19	1.02
4 t. carcasses pH_u<5.8	0.38	1.23	0.31	0.92
6-8 teeth carcasses	0.16	0.94	0.06	0.73
6-8 t. carcasses pH_u<5.8	-0.10	0.93	-0.14	0.71

Models were developed using simple regression procedure. R^2= coefficient of determination. RMSE=root mean square error

Table 4.18 Contingency table for WBSF 7 prediction using all male carcasses

Base line WBSF = 4.5 kg (n=163)		Base line WBSF = 3.4 kg (n=163)	
TPF n=98 60.12%	TNF n=27 16.56%	TPF n=17 10.43%	TNF n=91 55.83%
FNF n=22 13.50%	FPF n=16 9.82%	FNF n=44 27.00%	FPF n=11 6.74%
Accuracy= 76.68%(TPF+TNF) Sensitivity= 81.66% [TPF/(TPF+FNF)] Specificity= 62.77% [TNF/(FPF+TNF)]		Accuracy= 66.26% (TPF+TNF) Sensitivity= 27.87%[TPF/(TPF+FNF)] Specificity= 89.23%[TNF/(FPF+TNF)]	

Table 4.19 Contingency table for WBSF 14 prediction using all male carcasses

Base line WBSF = 4.5 kg (n=163)		Base line WBSF = 3.4 kg (n=163)	
TPF n=144 88.34%	TNF n=0	TPF n=51 31.29%	TNF n=48 29.45%
FNF n=0	FPF n=19 11.66%	FNF n=45 27.60%	FPF n=19 11.66%
Accuracy= 88.34% (TPF+TNF) Sensitivity= 100.00% [TPF/(TPF+FNF)] Specificity= 0.00% [TNF/(FPF+TNF)]		Accuracy= 60.74% (TPF+TNF) Sensitivity= 53.13% [TPF/(TPF+FNF)] Specificity= 71.64% [TNF/(FPF+TNF)]	

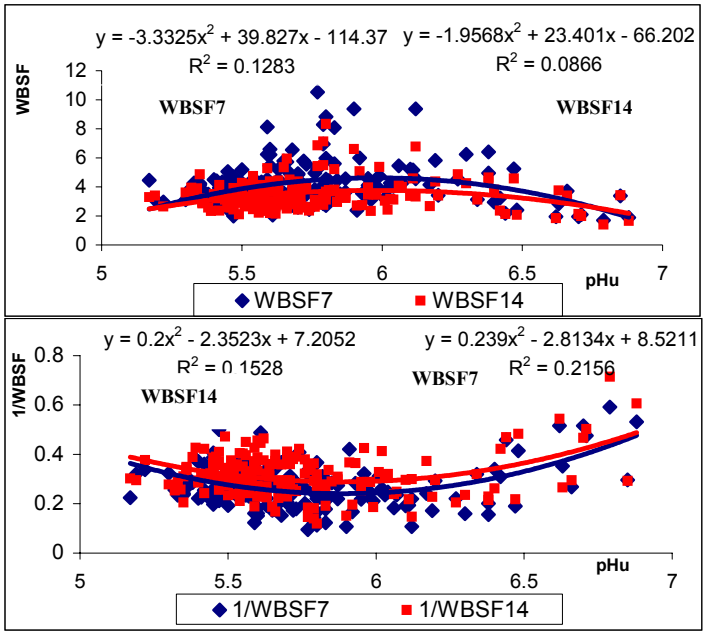

Fig 4.1 Quadratic response between WBSF (1/WBSF) and pH_u

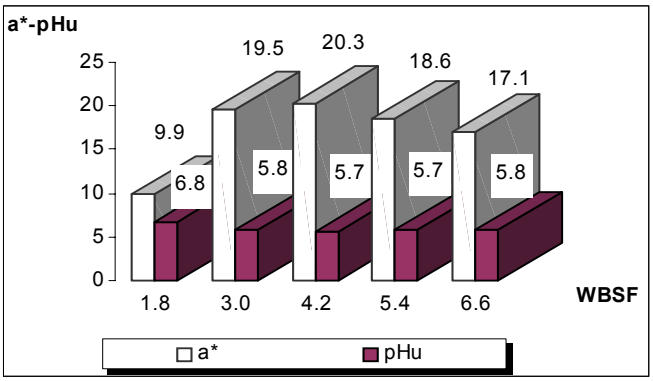

Fig 4.2 Lean a* and pH_u response with WBSF 7 values for all male carcasses

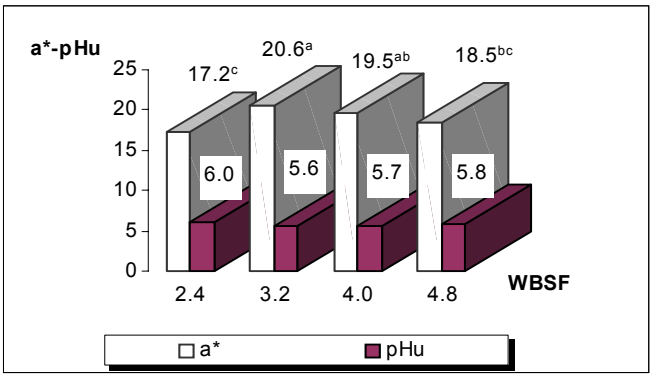

Fig 4.3 Lean a* and pH_u response with WBSF 14 values for all male carcasses

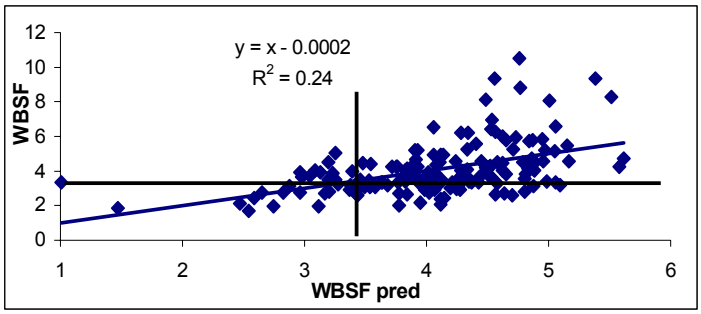

Fig 4.4 Relationship between WBSF 7 and predicted WBSF 7 (the horizontal and vertical lines correspond to WBSF = 3.4 kg) (Model: a, pH_u, pH_u^2)

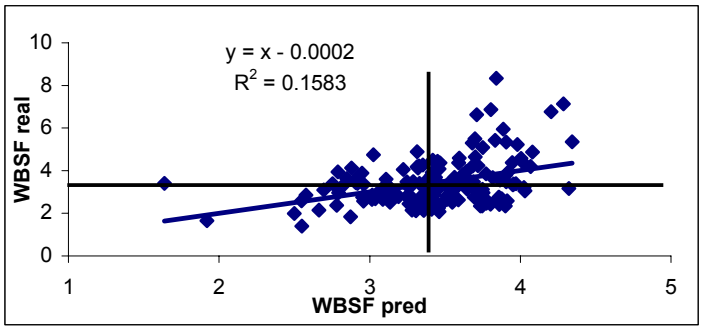

Fig 4.5 Relationship between WBSF 14 and predicted WBSF 14 (the horizontal and vertical lines correspond to WBSF = 3.4 kg) (Model: a, pH_u, pH_u^2)

CHAPTER 5

PREDICTING AND SEGREGATING BEEF TENDERNESS AMONG URUGUAYAN MALE CARCASSES IN TWO PACKING PLANTS UNDER COMMERCIAL CONDITIONS USING POSTMORTEM CARCASS TRAITS, pH, TEMPERATURE AND COLORIMETER READINGS [1]

[1] Brito, G. and D. Pringle. To be submitted to Journal of Animal Science

Abstract

The objectives of this study were to determine the relationships among carcass traits, pH, temperature and color in a male beef carcass population processed using Uruguayan commercial procedures and to determine whether these variables could be used to classify beef carcasses into tenderness categories. Four hundred forty-nine male beef carcasses of unknown origin were selected at two packing plants (PP) to represent the commercial conditions of the Uruguayan beef industry. Temperature (T_1, T_3 and T_u), pH (pH_1, pH_3 and pH_u) and colorimeter readings (L*, a* and b*) were collected postmortem. Longissimus muscle samples were removed from each carcass and Warner Bratzler shear forces were measured at 7 (WBSF7) and 14 days of aging (WBSF14). There was a significant effect of PP on tenderness ($P<0.01$). WBSF7 and WBSF14 showed high correlations (r) with T_u ($r= 0.43$ and 0.44, respectively, $P<0.01$). The correlation between a* and pH_u was -0.66 ($P<0.01$). Carcasses with $pH_3 < 5.8$, and a* values ≥ 20 showed the lowest level of WBSF ($P<0.01$) compared with carcasses in the range of 5.8-6.2 for pH_3 or with a* values < 20. A multiple linear regression equation developed with the variables dentition, ribeye area (REA), pH_u, T_u , L* ,a* and b* predicted WBSF7 and WBSF14 with an adjusted R^2 of 0.25 and 0.26, respectively. Analyzed this model within a PP showed a lower level of predicting tenderness, where other variables and their interactions may be affecting the results. An accuracy of 66.1% and 75.6% for WBSF7 and WBSF14 was observed in predicting whether a steak would be classified as tender using a WBSF threshold of 4.5 kg. Although QG, pH_u and a*, measured at ribbing, in Uruguayan commercial conditions can be used to differentiate levels of beef tenderness, however, other differences between PP must be considered that could impact the effectiveness of this method of segregation

Key Words: Beef, Male, Color, pH, Temperature, Tenderness

1. Introduction

As underscored by several authors, quality improvement must be driven by consumer expectations and perceptions. This makes sense; after all, consumers are the ultimate end -ser of the meat products. Different studies in North America have shown that most of the consumed beef is acceptable to the consumer, yet some is unacceptable, mostly because of its final tenderness (Jeremiah et al., 1991). The Beef Consumer Satisfaction study (Lorenzen et al., 1999; Savell et al., 1999) stated that tenderness can be a major contributor to consumer perception of quality, and consumers would be willing to pay for guaranteed tender beef steaks (Boleman et al., 1997). A good eating experience is essential to drawing the consumer back for another meat purchase, and hence, improving red meat buying trends. Uruguay and its meat industry, traditionally oriented to exporting most of its processed meat (60% approximately) as a *commodity*, should be concerned with this meat quality attribute and make efforts to identify the defects along the meat production chain. Improving these defects is critical, considering one of the meat industry goals is to enhance export opportunities in quality-based markets, such as Korea, Japan and NAFTA countries.

A practical, nondestructive procedure to distinguish palatable from unpalatable beef would be beneficial for this purpose. Several researchers have made attempts to effectively segregate beef carcasses into tough and tender groups. Some of them (Purchas et al 1990; Jeremiah et al., 1991; Wulf et al., 1997; Purchas et al., 1999) have demonstrated a relationship between ultimate muscle pH and/or color and meat tenderness measured either objectively (Warner-Bratzler shear force device) or subjectively (sensory trained and consumer panels). Wulf and Page (2000) reported that variables such as colorimeter readings, marbling, and hump height could be used as potential predictors of tenderness. Others authors have developed and applied technologies such as video image analysis or computer vision to detect differences in palatability, color (Belk et al., 2000; Vote et al., 2003) and textural properties (Li et al., 1999) of beef.

This research was conducted to characterize Uruguayan beef in tenderness and color, because no previous work exists and to study the effectiveness of using objective measures of muscle pH,

temperature, and color to predict tenderness on selected beef carcasses of unknown origin under commercial settings.

2. Materials and Methods

A group of 449 male beef carcasses of unknown origin were selected at two packing plants in Uruguay, in 2002. Carcasses were graded by the Uruguayan grading system (INAC, 1997) and selected at the time of grading. Carcasses were not electrically stimulated and were chosen based on three age classes by dentition (0-2 teeth, n=154, 4 teeth, n=206 and 8 teeth, n=89) and two fat thickness classes (≤ 6mm, n=263 and >6 mm, n=186). Carcasses were segregated into appropriate fat thickness categories based on actual carcass backfat measured at the 11th rib surface. The following carcass data also was collected at ribbing on the left side of the carcass at the 11th rib cut surface of the *longissimus dorsi*: ribeye area measured with a ribeye grid, lean colorimeter measures (L*, a*, b*), and muscle pH and temperature. Lean colorimeter readings were also collected one hour later to evaluate the effect of blooming. Following data collection, an 8-cm portion of the *longissimus dorsi* was removed from the left side of carcasses, labeled, vacuum-packaged and transported to the Meat Science Laboratory at INIA Tacuarembó for shear force analysis after 7 and 14 days of aging at 2 - 4 ^{o}C.

2.1 pH measurements

The pH of the *longissimus dorsi* was determined at three different times: 1, 3 and 18-24 (ultimate) h postmortem. The pH 1 and 3 h postmortem was measured between the 10 and 11th rib on the left side of the carcasses, at a depth of 2 cm. The measurement of ultimate pH was taken at the 11th rib cut surface in the pistol cut. The muscle pH was measured using a hand-held pH meter (Orion A 230) with a probe type electrode (BC 200, Hanna Instruments), standardized against two pH buffers (4 and 7). The probe was cleaned with cleaned with alcohol and rinsed with water between uses.

2.2 Temperature determination

The temperature was determined at 1, 3, and 18 - 24 h (ultimate) postmortem. In the first two measurements, the temperature was taken between the 10 and 11th rib on the left side of the carcasses. The ultimate temperature was collected at the 11th rib cut surface in the pistol cut. In each case, the

temperature was determined by a thermometer (Barnant 115) with stainless steel thermocouple (type E).

2.3 Muscle color determination

Muscle color measurements followed the CIE color convention (CIE, 1986), where the three fundamental outputs are L*, a* and b*. L* is lightness on a scale of 0 (all light absorbed) to 100 (all light reflected); a* spans from + 60 (red) to – 60 (green) and b* spans from + 60 (yellow) to – 60 (blue). Color measurements were made using a Minolta Colorimeter (model C-10) with a 50mm diameter measurement area. They were recorded in triplicate from the exposed *longissimus* muscle between the 10-11th rib immediately following ribbing (cutting between the 10-11th to expose the *longissimus* muscle) surface in the pistol cut (left side) and after 1 h post-ribbing to examine the effect of blooming on the three outputs (L*, a*, b*).

2.4 Warner-Bratzler Shear Force determination

The portions of *longissimus dorsi* transported to the Meat Science Laboratory at INIA Tacuarembó were aged for 7 and 14 days at 2-4 ^{o}C. At 7 d postmortem, the cuts were trimmed and sliced to generate 2.54 cm thick steaks. The first steak (at the anterior end) from each *longissimus* was used for shear force determination with 7 d of aging, the second was vacuum-packaged and aged another 7 days for subsequent Warner-Bratzler shear force analysis (WBSF), and the rest of the cut was frozen (-20^{o}C) for further analysis. The steaks aged 7 and 14 days were cooked by immersion in a plastic bag in a water bath (80 ^{o}C) to an internal temperature of 70^{o}C for 75 min. The internal temperature was monitored using type E thermocouples placed in the approximate geometric center of the steak.

Six cores (1.27 cm in diameter), parallel to the muscle fiber orientation, were removed from each steak. A single peak WBSF measurement was obtained for each core using a WBSF machine (G-R Electric Manufacturing Co, Manhattan, KS). Individual-core peak shear force values were averaged to assign a mean peak WBSF value to each steak.

2.5 Statistical analysis

Descriptive statistics were computed in this experiment for selected carcass traits, pH, temperature, colorimeter readings and WBSF values.

A Shapiro-Wilk test ($P<0.01$) from the Univariate procedure (SAS, 1990) was run to study whether these variables had a normal distribution.

The model used in this experiment was

$$Y_{ijklm} = \mu + A_i + B_j + C_k + D_l + ABCD_{ijkl} + E_{ijklm}$$

where

Y_{ijklm} = ijklmth Warner-Bratzler shear force at 7 and 14 days of aging,

μ = overall mean,

A_i = effect of the ith packing plant,

B_j = effect of the jth dentition,

C_k = effect of the kth hot carcass weight,

D_l = effect of the lth fat thickness,

$ABCD_{ijkl}$ = interaction effect of ijkl th packing plant*dentition * hot carcass weight*fat thickness

E_{ijklm} = residual error

Least squares means were calculated using the PDIFF procedure of SAS. To better understand the relationship between the independent and the dependent (WBSF values) variables the data were subjected to correlation and regression analysis, including multiple regression analysis computed by stepwise procedures (SAS, 1990). Objective muscle color measurements and muscle pH values were plotted against mean shear force values, and coefficients of determination (R^2) between these variables were obtained with the mentioned procedures. Contingency tables were analyzed to determine the efficacy of sorting carcasses by tenderness using the best model.

3. Results and Discussion

3.1 Carcass characteristics

Means, standard deviations, minimum and maximum values for HCW, Fat, REA, dentition, INAC conformation and finishing, pH and T at 1h and 3h postmortem, ultimate pH and T, lean L*, a* and b* values (without and with blooming) and WBSF with 7 and 14 days of aging are presented in Table 5.2. There were significant differences in WBSF 7 and WBSF 14 explained by packing plant ($P<0.01$) and the interactions between packing plant and dentition ($P<0.05$). Steaks from packing plant 1 (PP1) had lower ($P<0.01$) WBSF values at 7 and 14 days of aging than those from packing plant 2 (PP2) (Table 5.3). In both packing plants most of the carcasses were in the 4-teeth dentition group (PP1= 48% and PP2= 43%). The difference in tenderness could be related to the hot carcass weight and the thickness of subcutaneous fat. The cattle slaughtered in PP1 were heavier ($P<0.01$) and fatter ($P<0.01$) than the cattle from PP2 (Table 5.3). Shackelford et al. (1994a) showed that WBSF values were higher (5.58 vs. 5.32 kg, $P<0.01$) and trained sensory panel tenderness (TSPT) was lower (4.82 vs. 4.99, $P<0.01$) for carcasses with < 5mm subcutaneous fat thickness compared with those with ≥ 5mm, within a slight amount of marbling (Select). The authors concluded that the differences in WBSF and TSPT, however, were small and that an additional standard of ≥ 5mm fat thickness for the Select grade would not improve tenderness significantly.

Although in this research, breed was not taken in account as variable, the incidence of *Bos indicus* crossbred cattle was greater in PP2 than PP1, and this may partially explain the difference in finishing and aged tenderness. The carcasses evaluated in PP2 had higher ($P<0.01$) T_3, T_u, L*, a* and b* readings, and lower pH_u ($P<0.01$) than the carcasses slaughtered in PP1 (Table 5.3). Differences in the chilling process between packing plants may explain these results.

As the interaction PP*dentition was also significant in the model for WBSF, least square means and standard error for the significant variables are presented in Table 5.4. WBSF 7 and WBSF 14 were different ($P<0.01$) between PP for all PP*dentition combinations. The same trend was observed in the effect of PP for all variables described in Table 5.3 and 5.4, although statistical significance levels varied.

3.2 Correlation analyses

Simple correlations (P<0.01) of the variables, WBSF 7 and WBSF 14 and color parameters (L*, a* and b*) are presented in Table 5.5. T_u was the variable most closely related with WBSF 7 (r=0.43, P<0.01) and WBSF 14 (r=0.44, P< 0.01) when carcasses from both PP were analyzed. This is most likely due to differences in chilling processes between PP1 and PP2 since the PP1 carcasses were heavier, fatter, and had lower T_u than PP2 carcasses. T_3 also had low to moderate correlations with WBSF 7 (r=0.16, P<0.01) and WBSF 14 (r=0.27, P<0.01) in this study. The literature shows different results in this relationship. Shackelford et al. (1994b) observed no relationship (r=0.06) between temperature at 3 h (T_3=24.06 ^oC) and WBSF (5.61 kg) with 14 days of aging, while Jones and Tatum (1994) reported r=-0.11 between T_3 and WBSF 14. Lochner et al. (1980) found that the correlation between temperature and sensory panel tenderness increased as progressively shorter postmortem periods were considered, with the highest occurring between 2 and 4 h after slaughter (r= 0.78 and 0.76, respectively). No correlation between pH_u and WBSF 7 (r=-0.07) and WBSF 14 (r=-0.05) was found. Low to moderate (range r=0.08 to 0.29) correlations, however, are reported by the literature for both variables (Jones and Tatum, 1994; Eilers et al., 1996; Wulf et al., 1997; and Wulf and Page, 2000).

Within the color parameters, lean b* was low to moderately correlated (P<0.01) with both WBSF values. This positive correlation between lean b* and WBSF values is in disagreement with previous findings in female (r=-0.35 and -0.39 for WBSF 7 and WBSF 14, respectively) and male (r=-0.17 and -0.13, for WBSF 7 and WBSF 14 respectively) carcasses in PP1, where the correlation coefficient was negative. Wulf et al. (1997) and Vote et al. (2003) also found negative correlations between both variables in the range from -0.12 to -0.38, latter using CVS BeefCam lean b* output.

Related to muscle color, the results confirmed previous findings about the relationship between pH_u and colorimeter readings (mainly lean a* and b*). Wulf and Wise (1999) and Page et al. (2001) indicated that lean maturity is more associated to lightness/darkness, whereas muscle pH affects muscle color hue or color in the spectrum of red-green and yellow-blue. Ledward et al. (1992) explained that this relationship is based on the reflectance of light, where muscles with higher pH are

darker because there is less water to reflect light and by the oxygenation of the surface myoglobin (less oxygenation of this pigment occurs at higher meat pH). In this research, T_u and T_3 were moderately correlated with colorimeter readings, with the highest correlation (r=0.42) between T_u and b*.

3.3. Relationship between pH_3 and tenderness and color.

Some evidence has shown that a curvilinear relationship exists between early post-mortem pH and tenderness (Hwang and Thompson, 2001; Pike et al., 1993; Marsh et al., 1987). For these studies, an intermediate pH decline (pH_3= 5.9-6.2) produced the most tender meat and the longest sarcomeres. In this research, however, the lowest WBSF were obtained in the carcass group with $pH_3 < 5.8$ (Table 5.6), either considering all carcasses or carcasses with $pH_u < 5.8$. This is concordant with the results obtained by Marshall and Tatum (1991). These authors, cited by Shackelford et al. (1994b), tested the efficacy of pH_3 as a predictor of beef palatability in commercial packing plants and found that the most tender beef was achieved when pH_3 was below 5.8.

In Marshall and Tatum's (1991) study as in Shackelford's et al. (1994b) research, pH_3 was not highly correlated with tenderness (r=0.16 and 0.03, respectively) and it was not effective in grouping carcasses by tenderness. The same result was reported by Eilers et al. (1996) with a coefficient correlation r=0.08 between these variables (pH_3 and WBSF 14).

Within colorimeter parameters, pH_3 showed the highest correlation with lean a* (Table 5.6). When all carcasses were analyzed the $pH_3 > 6.2$ group had the darkest lean a* color ($P<0.01$), primarily associated with DFD carcasses. When the carcasses with $pH_u > 5.8$ were eliminated, no differences ($P>0.05$) in lean a* were found among pH_3 groups.

3.4 Relationship between pH_u and tenderness and color

The response observed between pH_u and WBSF (7 and 14 days of aging) had a low R^2 using a 2^{nd} order-equation (R^2= 0.04 and 0.003 for WBSF 7 and WBSF 14, respectively), yet higher WBSF values were obtained in the range of pH_u 5.8-6.2 (Fig. 5.1).

The relationship between ultimate pH and tenderness is, however, controversial. Some authors (Bouton et al., 1973; Guignot et al., 1994; Silva et al., 1999) found a linear relationship

between these two parameters, whereas others (Purchas, 1990; Jeremiah et al., 1991; Purchas and Aungsupakorn, 1993; Wulf et al., 1997) found a curvilinear relationship with minimum tenderness occurring between pH 5.8 and 6.2.

Several hypotheses have been proposed to explain this curvilinear relationship and the reasons have not been adequately explained. Yu and Lee (1986) suggested a differential proteolytic activity was responsible for the toughness of meat of pH 5.8-6.3. There is less activity of these enzymes at intermediate final pH values because this range lies outside the pH optima of two separate enzyme systems. The increased tenderness found as the ultimate pH rises from 6 to 7 was attributed to greater calpain activity, which is maximal at neutral pH. At intermediate pH values, the pH is neither optimal for calpains nor for cathepsin activity, resulting in the lowest degree of meat tenderization during aging.

It has been suggested that the lysosomal enzyme activity may be responsible for the tenderization process as the pH falls from 6 to 5.4 because their optima pH are found in these lower ranges. However, there is significant evidence accumulated in which post-mortem tenderization is Ca^{2+}- (Koohmaraie et al., 1988) and calpain-dependent (Koohmaraie, 1990; Dransfield, 1993), while inhibition of lysosomal enzyme activity has little effect on tenderness, even when ultimate pH is in the low range (Koohmaraie et al., 1988).

Different Uruguayan export markets require carcasses with $pH_u < 5.8$ in the *longissimus dorsi* muscle. Based on this requirement, the observed response between WBSF and pH_u, and the usual pH_u groups presented in the literature, this study segregated carcass into three pH groups**,** normal (N: $pH_u < 5.8$), moderate dark (MD: $pH_u = 5.8$-6.2) and DFD ($pH_u > 6.2$) in Table 7. Analyzing the distribution of the carcasses in each group for all carcasses and each PP, 73-89% of them were in N group, 11-20% in MD group, and only 4-7% classified DFD (PP2 had only one carcass with $pH_u > 6.2$). The MD group always had the toughest steaks for both WBSF 7 and WBSF 14. For WBSF 7, the MD carcass group was significantly different ($P<0.01$) from the other two, for all carcasses in PP1.

For WBSF 14, the same group was only different ($P<0.01$) from DFD, again for all carcasses and in PP1. No differences ($P>0.05$) in WBSF were found among pH_u groups in PP2. A high correlation between pH_u and colorimeter readings, mainly with lean a* ($r=-0.66$) was noted (Fig. 5.1).

The N group presented lean a* mean values higher than 20, followed by MD group with lean a* values between 17 and 18. N group was different in lean a* ($P<0.01$) from MD group, for all scenarios (Table 5.7). DFD group presented the darkest color (lean a*=13 or lower). According to this information and basic statistics (mean and median of our carcass population), a threshold of 20 for lean a* was used to observe whether a*-based differences in WBSF exist (Table 5.8). The carcasses with lean a* values < 20 had higher WBSF 7 ($P<0.01$) and WBSF 14 ($P<0.05$) than the carcass group with a* values ≥ 20, either when all carcasses or carcasses with $pH_u<5.8$ were considered (including both PP). The response was observed in a previous study conducted in PP1 with female and male carcasses. Studying the response of pH_u and lean a* with the increase of WBSF (Fig. 5.2 and 5.3, for WBSF 7 and WBSF 14, respectively), it appears that for all carcasses, neither pH_u nor lean a* could differentiate carcasses by level of tenderness. Ultimate pH and lean a* values were not significantly different ($P<0.05$) for the different levels of tenderness measured by WBSF when the first column, which represents DFD carcasses, was not considered (Fig 5.2 and 5.3).

3.5 Regression analyses

Multiple regression equations developed for prediction of WBSF using stepwise procedure are presented in Table 5.9 for all carcasses and Table 5.10 for carcasses with pH<5.8. Three scenarios for this prediction were taken into account: all carcasses (both PP), PP1 and PP2. When all carcasses were analyzed, the first variable in entering into the model was T_u either for WBSF 7 or WBSF 14 (partial R^2 in the range of 0.18 to 0.20). This is most likely due to the mentioned differences in final temperature and WBSF between PP. The rest of the variables entering in the model for both aging times and all carcasses were Rea, T_1, pH_1, pH_u, dentition, and L*.

The main variables to explain the WBSF variation in each PP varied. Lean a* and pH (at the 3 times) were the principal variables and accounted for the WBSF variation (7 and 14 days of aging) in

PP1 (Table 5.10). In the prediction of WBSF 7, lean a* had a partial R^2= 0.19 for carcasses with pH_u<5.8, and pH_3 and pH_u explained an additional 6% of this variation.

Jeremiah et al. (1991) reported low coefficients of determination in steer carcasses (R^2= 0.07) when pH_u, subjective and objective color measurements were included in the model. However, Wulf et al. (1997) found a R^2= 0.20 using lean L*, a* and b* colorimeter readings and pH_u. Considering all carcasses, the R^2 of the WBSF 7 model was low and lean a* only accounted for 6% of the tenderness variation (Table 5.9). For WBSF 14, pH_1 alone accounted for 23% of WBSF variation, followed by lean a* and T_u in carcasses with pH_u <5.8 (Table 5.10) and 11% of the variation when analyzing all carcasses (Table 5.9).

In PP2, pH_1 for WBSF 7 prediction (partial R^2=0.16) and T_3 for WBSF 14 prediction (partial R^2=0.16), were the first variables to meet the significance levels in stepwise procedure**.** Shackelford et al. (1994b) did not find any relationship between T_3 and WBSF 7; however, Lochner et al. (1980) reported that tenderness was highly dependent on early (2 - 4 h) postmortem temperature. These authors supported this finding on the toughness because a low degree of finishing could be counteracted by altering the cooling conditions during early postmortem periods, and a less rigorous early chilling process usually results in tenderness improvement.

Based on the information obtained in Tables 5.9 and 5.10 and the practical application of it in a commercial packing plant, a model was constructed to predict WBSF with the following variables: dentition, Rea, pH_u, T_u, L*, a* and b*. The models to predict WBSF 7 and WBSF 14 were :

WBSF 7=13.77 - 0.188*dentition + 0.05*Rea - 1.047*pH_u + 0.275*T_u - 0.165*lean L* - 0.07*lean a* + 0.08*lean b*

WBSF 14= 7.94 - 0.161*dentition + 0.03*Rea - 0.378*pH_u + 0.235*T_u - 0.108*lean L* - 0.07*lean a* + 0.08*lean b*

This model showed a similar adjusted R^2 (adj. R^2) either for WBSF 7 and WBSF 14 (Table 5.11). When carcasses with pH_u > 5.8 were not considered, an increase of 5% was observed in the adj. R^2 for both WBSF predictions. These variables better contribution explained tenderness variation in PP1 than PP2. For PP1, considering only carcasses with pH_u < 5.8 resulted in a better prediction

(higher adj. R^2) of tenderness than the analysis with all carcasses (adj. R^2= 0.22-0.28 vs. 0.10-0.17, respectively for each aging period, 7 and 14 days).

The model applied in PP2 had, in general, poor performance, having a higher adj. R^2 for WBSF 14 than WBSF 7.

The relationship between real WBSF (for both aging times) and predicted WBSF using the mentioned model is presented in Fig. 5.4 (WBSF 7) and 5.5 (WBSF 14). The R^2 for both predictions was 0.27. Horizontal and vertical lines for a WBSF threshold of 4.5 kg were drawn to visualize the degree of prediction and each component of the contingency tables.

3.6 Contingency Tables

A means of determining whether this model can predict aged tenderness in these carcasses, is by constructing contingency tables. An arbitrary WBSF threshold at evaluation is selected for a decision point. The estimate of the accuracy is based on a true positive fraction (TP: tender) or animals correctly predicted according to the specified WBSF threshold plus true negative fraction (TN: tough) or animals correctly predicted above this category. Sensitivity (actually positive cases) and specificity (actually negative cases) represent two kinds of accuracy. Shackelford et al. (1991) published that the transition between tough and tender steaks occurred at a WBSF of 4.5 kg when this objective measurement was related to sensory data. This was confirmed by Miller et al. (2001) who reported an average transition of 4.6 kg. These authors also studied the consumer acceptability of beefsteak tenderness and obtained a 99% consumer satisfaction rating with a WBSF value of 3.4 kg.

Four combinations, two WBSF thresholds and two aging periods, were selected to determine the accuracy of the model (Table 5.12 and 5.13). Clearly these tables show the dependence on the WBSF threshold used. For WBSF 7, the accuracy was better using a WBSF threshold of 3.4 kg than 4.5 kg (Table 5.12). In both thresholds, the accuracy could be obtained by specificity (true negative fraction: high proportion of tough steaks).

The contingency tables to predict WBSF 14 present higher accuracy (75.60%) when the threshold was 4.5 kg than 3.4 kg (68.24%). In this case, sensitivity (positive fraction) was more

accurate than specificity for WBSF threshold of 4.5 kg, and, in contrast, specificity was most accurate (84.26%) for 3.4 kg critical WBSF point.

4. Implications

This study evaluated carcass traits, muscle pH, temperature and color as potential predictors of tenderness under commercial conditions in two packing plants. The best individual variable to explain the variation in tenderness for all selected carcasses was ultimate temperature. Differences in tenderness were found between both packing plants; however, the effect of temperature on the final WBSF values could be confounded with the different types of cattle (breed and degree of finishing) that were processed in each packing plant. The addition of other variables such as muscle pH, color and ribeye area increased the accuracy of sorting carcasses into tough or tender groups. The effectiveness of colorimeter readings to segregate carcasses by tenderness in this research was not acceptable, although in other scenarios muscle color may be an effective critical control point in the process of ensuring tender beef. Further investigation should be conducted to determine whether accurate non-invasive methods to predict tenderness in Uruguayan cattle could be developed, thus identifying carcasses likely to produce tender steaks under commercial conditions. The effects of electrical stimulation on these methods should also be evaluated. It should also be determined whether application of these methodologies in emerging branded beef programs, to improve palatability and consistency of the product, is valuable.

Literature Cited

Belk, K.E., J.A. Scanga, A.M. Wyle, D.M. Wulf, J.D. Tatum, J.O. Reagan, and G.C. Smith 2000. The use of video image analysis and instrumentation to predict beef palatability Proc. Recip. Meat Conf. 53:10-15.

Boleman, S.J., S.L. Boleman, R.K. Miller, J.F. Taylor, H.R. Cross, T.L. Wheeler, M. Koohmaraie, S.D. Shackelford, M.F. Miller, R.L. West, and J.W. Savell. 1997. Consumer evaluation of beef of known categories of tenderness. J. Anim. Sci. 75:1521-1524.

Bouton, P.E., F.D. Carroll, P.V. Harris, and W.R. Shorthose. 1973. Influence of pH and fiber contraction state upon factors affecting the tenderness of bovine muscle. J. Food Sci. 38:404-407.

Dransfield, E. 1993. Modelling post-mortem tenderization-IV: Role of calpains and calpastatin in conditioning. Meat Sci. 34:217-234.

C.I.E., 1986. Colorimetry (2nd ed.) Commission International de l'Éclairage, Publication CIE 15.2. Vienna: CIE.

Eilers, J.D., J.D. Tatum, J.B. Morgan, and G.C. Smith. 1996. Modification of early-postmortem muscle pH and use of postmortem aging to improve beef tenderness. J. Anim. Sci. 74:790-798.

Guignot, F., C. Touraille, A. Ouali, and M. Renerre, 1994. Relationships between post-mortem pH changes and some traits of sensory quality in veal. Meat Sci. 37:315-325.

Hwang, I.H., and J.M. Thompson. 2001b. The interaction between pH and temperature decline early post-mortem on the calpain system and objective tenderness in electrically stimulated beef *longissimus dorsi* muscle. Meat Sci. 58:167-174.

I.N.A.C. (1997). Sistema oficial (uruguayo) de clasificación y tipificación de carne vacuna. Resolución 65/97. Montevideo, Uruguay.

Jeremiah, L.E., A.K. Tong, and L.L. Gibson. 1991. The usefulness of muscle color and pH for segregating beef carcasses into tenderness groups. Meat Sci. 30: 97-114.

Jones, B.K. and J.D. Tatum. 1994. Predictors of beef tenderness among carcasses produced under commercial conditions. J. Anim. Sci. 72:1492-1501.

Koohmaraie, M. 1988. The role of endogenous proteases in meat tenderness. Proc. Recip. Meat Conf. 41:89-99.

Koohmaraie, M, G. Whipple, and J.D. Crouse. 1990. Acceleration of post-mortem tenderization in lamb and Brahman-cross beef carcasses through infusion of calcium chloride. J. Anim. Sci. 68:1278-1283.

Ledward, D.A. 1992. Color of the raw and cooked meat. In D.E. Johnston, M. Knight, and D.A. Ledward. *The chemistry of muscle based foods*. Cambridge, UK:Royal Society of Chemistry .pp:128-144.

Li, J., J. Tan, F.A. Martz, and H. Heymann. 1999. Image texture features as indicators of beef tenderness. Meat Sci. 53:17-22.

Lochner, J.V., R.G. Kauffman, and B.B. Marsh. 1980. Early post-mortem cooling rate and beef tenderness. Meat Sci. 4:227-241.

Lorenzen, C.L., T.R. Neely, R.K. Miller, J.D. Tatum, J.W. Wise, J.F. Taylor, M.J. Buyck, J.O. Reagan, and J.W. Savell. 1999. Beef Customer Satisfaction: Cooking method and degree of doneness effects on the top loin steak. J.Anim.Sci. 77:637-644.

Marsh, B.B., T.P. Ringkob, R.L. Russell, D.R. Swartz, and L.A. Pagel. 1987. Effects of early-postmortem glycolytic rate on beef tenderness. Meat Sci. 21:241-248.

Miller, M.F., M.A. Carr, C.B. Ramsey, K.L. Crockett, and L.C. Hoover. 2001. Consumer thresholds for establishing the value of beef tenderness. J. Anim.Sci. 79:3062-3068.

Page, J.K., D.M. Wulf, and T.R. Schwotzer. 2001. A survey of beef muscle color and pH. J. Anim. Sci. 79:678-687.

Pike, M.M., T.P. Ringkob, D.D. Beekman, Y.O. Koh, and W.T. Gerthoffer. 1993. Quadratic relationship between early post-mortem glycolytic rate and beef tenderness. Meat Sci. 34:13-26.

Purchas, R.W. 1990. An assessment of the role of pH differences in determining the relative tenderness of meat from bulls and steers. Meat Sci. 27:129-140.

Purchas, R.W., and R. Aungsupakorn. 1993. Further investigations into the relationship between ultimate pH and tenderness of beef samples from bulls and steers. Meat Sci. 34:163-178.

Purchas, R. W., X. Yan, and D.G. Hartley. 1999. The influence of a period of aging on the relationship between ultimate pH and shear values of beef *m. longissimus thoracis.* Meat Sci. 51:135-141.

Savell, J.W., C.L. Lorenzen, T.R. Neely, R.K. Miller, J.D. Tatum, J.W. Wise, J.F. Taylor, M.J. Buyck, and J.O. Reagan. 1999. Beef Customer Satisfaction: Cooking method and degree of doneness effects on the top sirloin steak. J.Anim.Sci. 77:645-652.

Shackelford, S.D, M. Koohmaraie, G. Whipple, T.L. Wheeler, M.F. Miller, J.D. Crouse, and J.O. Reagan. 1991. Predictors of beef tenderness: Development and verification. J. Food Sci. 56(5):1130-1135.

Shackelford, S.D., M. Koohmaraie, and T.L. Wheeler. 1994a. The efficacy of adding a minimum adjusted fat thickness requirement to the USDA beef quality grading standards for select grade beef. J. Anim. Sci. 72:1502-1507.

Shackelford, S.D., M. Koohmaraie, and J.W. Savell. 1994b. Evaluation of *longissimus dorsi* muscle pH at three hours post-mortem as a predictor of beef tenderness. Meat Sci. 37: 195-204.

Silva, J.A., L. Patarata, and C. Martins. 1999. Influence of ultimate pH on bovine meat tenderness during aging. Meat Sci. 52:453-459.

Vote, D.J., K.E. Belk, J.D. Tatum, J.A. Scanga, and G.C. Smith. 2003. Online prediction of beef tenderness using a computer vision system equipped with a BeefCam module. J. Anim. Sci. 81:457-465.

Wulf, D.M., S.F. O'Connor, J. D. Tatum, and G. C. Smith. 1997. Using objective measures of muscle color to predict beef *longissimus* tenderness. J. Anim. Sci. 75:684-692.

Wulf, D.M., and J.W. Wise. 1999. Measuring muscle color on beef carcasses using the L* a* b* color space. J. Anim. Sci. 77:2418-2427.

Wulf, D.M. and J.K. Page. 2000. Using measurements of muscle color, pH, and electrical impedance to augment the current USDA beef quality grading standards and improve the accuracy and precision of sorting carcasses into palatability groups. J. Anim. Sci. 78:2595-2607.

Yu, L.P., and Y.B. Lee. (1986). Effects of post-mortem pH and temperature on bovine muscle structure and meat tenderness. J. Food Sci. 51:774-780.

Table 5.1 Definition of variables

Variable	Definition
PP	Packing Plant
Con	INAC Conformation 1=I (best conf.) to 6=R (worst conf.)
Fin	INAC Finishing 0=low fat to 3=high fat
Dentition	Dentition 0, 2, 4, 6, 8 teeth
HCW	Hot carcass weight (kg)
Fat	Subcutaneous fat between 10-11th rib (mm)
Rea	Rib eye area (cm^2)
pH_1 pH_3 pH_u	pH at 1, 3, 18-24 h postmortem
T_1 T_3 T_u	Temperature at 1, 3, 18-24 h postmortem (^oC)
L*	Luminance 0=black to 100= white
a*	+60= red to –60=green
b*	+60= yellow to –60=blue
Lb* ab* bb*	L*, a*, b* with 1 h of blooming time after ribbing
WBSF 7	Warner-Bratzler shear force with 7 days of aging (kg)
WBSF 14	Warner-Bratzler shear force with 14 days of aging (kg)

Table 5.2 Mean and Standard deviation of main variables in all male carcasses.

Variable	Mean	Std Dev	Minimum	Maximum
Con	3.10	0.48	2	4
Fin	1.78	0.47	0	3
Dentition	3.79	1.92	0	8
HCW	243.15	28.73	179	374.2
Fat	6.24	3.90	0	20
Rea	57.17	8.17	30.48	85.27
pH_1	6.23	0.32	5.45	7.28
pH_3	5.95	0.27	5.26	6.90
pH_u	5.67	0.26	5.17	6.88
T_1	35.05	3.11	23.10	42.40
T_3	23.18	3.94	11.20	36.40
T_u	4.33	3.13	0.10	14.00
L*	32.19	3.20	23.12	41.07
a*	20.24	3.40	9.85	32.30
b*	9.47	2.58	3.40	28.13
Lb*	33.21	3.22	23.60	41.70
ab*	22.32	3.74	10.83	33.45
bb*	11.13	2.59	4.07	18.90
WBSF7	4.83	1.94	1.69	13.32
WBSF14	4.14	1.59	1.40	12.58

Table 5.3 Least Squares Means and Standard Error ( )for significant variables by packing plant

Pack	WBSF7	WBSF14	HCW	Dent.	Fat	Rea	T_3	T_u	pH_u	L*	a*	b*
1	3.87^{c} (0.17)	3.60^{c} (0.15)	246.42^{a} (1.78)	4.00^{a} (0.12)	6.99^{a} (0.24)	54.52^{c} (0.49)	22.44^{c} (0.24)	2.74^{c} (0.16)	5.72^{a} (0.02)	31.48^{c} (0.20)	19.43^{c} (0.21)	8.75^{c} (0.16)
2	5.74^{a} (0.19)	4.79^{a} (0.17)	238.82^{c} (2.05)	3.53^{b} (0.14)	5.26^{c} (0.27)	60.78^{a} (0.58)	24.15^{a} (0.28)	6.42^{a} (0.18)	5.60^{c} (0.02)	33.11^{a} (0.22)	21.27^{a} (0.24)	10.39^{a} (0.18)

^{a,b,c} Means in the same column comparing variables by packing plant bearing a common superscript letter are not significantly different ($P<0.05$). Means in the same column comparing variables by packing plant with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 5.4 Least Squares Means and Standard Error ( ) for measured variables by packing plant *dentition interaction

Dentition	**0-2 teeth** (n=154)		**4 teeth** (n=206)		**6-8 teeth** (n=89)	
PP	**1** (n=80)	**2** (n=74)	**1** (n=123)	**2** (n=83)	**1** (n=53)	**2** (n=36)
HCW	237.08 (3.09)	234.08 (3.21)	245.80 (2.49)	238.13 (3.03)	261.96[a] (3.79)	250.17[b] (4.60)
Rea	56.10[c] (0.94)	61.57[a] (0.97)	54.3[c] (0.69)	59.92[a] (0.83)	53.05[c] (10.4)	61.51[a] (1.38)
Rea/hcw	12.11[c] (0.17)	13.09[a] (0.18)	11.14[c] (0.13)	12.63[a] (0.16)	10.20[c] (0.19)	12.17[a] (0.26)
Fat	7.21[a] (0.42)	4.89[c] (0.44)	6.41[a] (0.34)	5.27[b] (0.42)	8.00[a] (0.52)	5.99[b] (0.63)
T_3	22.93[c] (0.43)	25.04[a] (0.44)	22.17 (0.35)	23.00 (0.42)	22.31[c] (0.53)	24.95[a] (0.63)
T_u	2.11[c] (0.28)	5.43[a] (0.29)	2.97[c] (0.23)	6.70[a] (0.27)	3.18[c] (0.34)	7.81[a] (0.41)
pH_u	5.69 (0.03)	5.62 (0.03)	5.74[c] (0.02)	5.61[a] (0.03)	5.70[b] (0.03)	5.57[a] (0.04)
L	33.45 (0.34)	32.72 (0.34)	30.95[c] (0.27)	33.36[a] (0.32)	29.84[c] (0.41)	33.34[a] (0.49)
a*	19.48[c] (0.37)	22.14[a] (0.38)	18.99[c] (0.30)	20.50[a] (0.36)	20.38 (0.45)	21.27 (0.54)
b*	8.75[c] (0.28)	10.98[a] (0.28)	8.50[c] (0.22)	9.92[a] (0.27)	9.34 (0.34)	10.29 (0.41)
WBSF7	3.85[c] (0.19)	6.12[a] (0.20)	4.27[c] (0.16)	5.39[a] (0.19)	3.76[c] (0.24)	6.16[a] (0.28)
WBSF14	3.57[c] (0.17)	5.06[a] (0.17)	3.84[c] (0.13)	4.52[a] (0.17)	3.44[c] (0.20)	5.03[a] (0.29)

[a,b,c] Means in the same row comparing packing plant bearing a common superscript letter are not significantly different ($P<0.05$). Means in the same row comparing packing plant with one letter of difference differ ($P<0.05$), with more than one letter of difference differ ($P<0.01$)

Table 5.5 Main simple correlations between carcass variables and tenderness and color for all male carcasses

Variable	WBSF7	WBSF14	Variable	L*	a*	b*
Rea	0.25**	0.25**	**HCW**	-	0.13**	0.13**
pH_1	0.23**	0.27**	**Rea**	0.29**	0.24**	0.26**
pH_3	0.16**	0.14**	**pH_3**	-0.29**	-0.33**	-0.22**
T_3	0.16**	0.27**	**pH_u**	-0.59**	-0.66**	-0.59**
T_u	0.43**	0.44**	**T_3**	0.24**	0.28**	0.29**
b*	0.16**	0.18**	**T_u**	0.29**	0.26**	0.42**

** Significative at 1%

Table 5.6 Least square means and Standard error ( ) between pH_3 classes and WBSF and lean a* for all carcasses and carcasses with pH_u<5.8

	All carcasses			Carcasses pH_u<5.8		
pH_3	**WBSF 7**	**WBSF14**	**a***	**WBSF 7**	**WBSF14**	**a***
< 5.8	4.35[c]	3.72[c]	21.23[a]	4.38[d]	3.72 [c]	21.39
	(0.16)	(0.14)	(0.29)	(0.16)	(0.14)	(0.25)
5.8 – 6.2	4.92[a]	4.23[a]	20.27[c]	4.95[c]	4.25[b]	21.04
	(0.11)	(0.09)	(0.20)	(0.12)	(0.11)	(0.19)
> 6.2	5.37[a]	4.52[a]	18.56[d]	5.93 [a]	4.93[a]	20.80
	(0.21)	(0.18)	(0.37)	(0.28)	(0.24)	(0.40)

[a,b,c,d] Means in the same column bearing a common superscript letter are not significantly different (P<0.05)
Means in the same column with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 5.7 Least square means and Standard error ( ) between pH_u groups and WBSF and lean a*

	All carcasses			PP 1			PP 2		
pH_u	**WBSF 7**	**WBSF14**	**a***	**WBSF 7**	**WBSF14**	**a***	**WBSF 7**	**WBSF14**	**a***
< 5.8	4.75[c]	4.09 [bc]	21.12[a]	3.87[c]	3.65abc	20.65 [a]	5.80	4.74	21.73 [a]
	(0.09)	(0.08)	(0.14)	(0.10)	(0.09)	(0.17)	(0.16)	(0.15)	(0.24)
5.8 – 6.2	5.39[a]	4.57 [a]	17.57[c]	4.77[a]	3.98[a]	17.24[c]	5.93	5.54	17.87[c]
	(0.20)	(0.18)	(0.33)	(0.19)	(0.17)	(0.33)	(0.45)	(0.39)	(0.68)
> 6.2	4.15[c]	3.47[c]	13.10[d]	3.38[c]	3.10 [c]	12.61[e]	4.47	2.57	14.43[bc]
	(0.40)	(0.34)	(0.62)	(0.32)	(0.28)	(0.53)	(2.06)	(1.81)	(3.09)

[a,b,c] Means in the same column bearing a common superscript letter are not significantly different (P<0.05)
Means in the same column with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 5.8 Least square means, and Standard error ( ) between WBSF and color (a*) for all male carcasses and carcasses with pH_u<5.8

	All carcasses				All carcasses pH_u < 5.8			
a*	**n**	**WBSF 7**	**WBSF14**	**pH_u**	**n**	**WBSF 7**	**WBSF14**	**pH_u**
< 20	198	5.18[a]	4.32 [a]	5.81 [a]	124	5.35[a]	4.39[a]	5.64[a]
		(0.12)	(0.11)	(0.02)		(0.16)	(0.14)	(0.01)
≥ 20	251	4.55[c]	3.99 [b]	5.56[c]	241	4.62[c]	4.03[b]	5.54[c]
		(0.11)	(0.10)	(0.01)		(0.11)	(0.10)	(0.01)

[a,b,c] Means in the same column with one letter of difference differ (P<0.05), with more than one letter of difference differ (P<0.01)

Table 5.9 Multiple regression equations to predict WBSF 7 and WBSF 14 using all male carcass traits for all carcasses and for each packing plant

WBSF 7			**WBSF14**		
Independent variables	**R^2**	**RMSE**	**Independent variables**	**R^2**	**RMSE**
All carcasses					
T_u	0.18	1.81	T_u	0.20	1.49
T_u, Rea	0.21	1.77	T_u, T_1	0.23	1.46
T_u, Rea, pH_1	0.24	1.75	T_u, T_1, dentition	0.25	1.45
T_u, Rea, pH_1, dentition	0.26	1.73	T_u, T_1, dentition, L*	0.27	1.42
T_u, Rea, pH_1, dentition, L*	0.27	1.71	T_u, T_1, dentition, L*, Rea	0.28	1.41
PP 1					
a*	0.06	1.32	pH_1	0.11	1.19
a*, pH_u	0.11	1.14	pH_1, Rea	0.15	1.17
a*, pH_u, Rea	0.13	1.35	pH_1, Rea, pH_3	0.17	1.15
			pH_1, Rea, pH_3,a*	0.19	1.14
PP 2					
pH_1	0.16	1.92	T_3	0.14	1.78
pH_1, dentition	0.18	1.90	T_3, pH_1	0.17	1.75
pH_1, dentition, L*	0.19	1.89	T_3, pH_1, pH_u	0.21	1.72
pH_1, dentition, L*, b*	0.21	1.87	T_3, pH_1, pH_u, T_1	0.24	1.69

Models were developed using stepwise procedure. R^2= coefficient of determination. RMSE=root mean square error

Table 5.10 Multiple regression equations to predict WBSF 7 and WBSF 14 using all male carcass traits (pH_u<5.8)for all carcasses and for each packing plant

WBSF 7			**WBSF14**		
Independent variables	**R^2**	**RMSE**	**Independent variables**	**R^2**	**RMSE**
All carcasses					
T_u	0.19	1.84	T_u	0.20	1.53
T_u, pH_1	0.25	1.77	T_u, pH_1	0.25	1.77
T_u, pH_1, pH_u	0.28	1.73	T_u, pH_1, dentition	0.29	1.44
T_u, pH_1, pH_u, Rea	0.31	1.71	T_u, pH_1, dentition, pH_u	0.33	1.41
T_u, pH_1, pH_u, Rea, L*	0.33	1.69	T_u, pH_1, dentition, pH_u, L*	0.34	1.39
Packing plant 1					
a*	0.19	1.21	pH_1	0.23	1.14
a*, pH_3	0.23	1.19	pH_1, a*	0.25	1.13
a*, pH_3, pH_u	0.25	1.18	pH_1, a*, T_u	0.29	1.10
a*, pH_3, pH_u, L*	0.26	1.17	pH_1, a*, T_u, Rea	0.32	1.08
a*, pH_3, pH_u, L*, pH_1	0.27	1.17	pH_1, a*, T_u, Rea, pH_u	0.33	1.07
Packing plant 2					
pH_1	0.16	1.94	T_3	0.14	1.80
pH_1, dentition	0.19	1.92	T_3, pH_1	0.19	1.76
pH_1, dentition, pH_u	0.21	1.90	T_3, pH_1, pH_u	0.26	1.69
pH_1, dentition, pH_u, b*	0.22	1.89	T_3, pH_1, pH_u, T_1	0.30	1.65

Models were developed using stepwise procedure. R^2= coefficient of determination.
RMSE=root mean square error

Table 5.11 Simple regression equations to predict WBSF 7 and WBSF 14 using selected variables by stepwise procedure for all carcasses

Dependent variables	**WBSF 7**		**WBSF 14**	
Model 1 = dentition, Rea, pH_u, T_u, L*, a*, b*				
	adj-R^2	**RMSE**	**adj-R^2**	**RMSE**
All carcasses	0.25	1.72	0.26	1.43
All carcasses pH_u<5.8	0.30	1.71	0.31	1.42
Packing plant 1	0.10	1.36	0.17	1.15
Packing plant 1 pH_u<5.8	0.22	1.19	0.28	1.10
Packing plant 2	0.12	1.95	0.20	1.72
Packing plant 2 pH_u<5.8	0.11	1.98	0.21	1.72

Models were developed using simple regression procedure. R^2= coefficient of determination. RMSE=root mean square error

Table 5.12 Contingency table for WBSF 7 prediction using all male carcasses

Base line WBSF = 4.5 kg (n=380)		Base line WBSF = 3.4 kg (n=380)	
TPF n=87 22.90%	TNF n=164 43.16%	TPF n=3 0.80%	TNF n=294 77.36%
FNF n=106 27.90%	FPF n=23 6.04%	FNF n=82 21.58%	FPF n=1 0.26%
Accuracy= 66.06%(TPF+TNF) Sensitivity= 45.08% [TPF/(TPF+FNF)] Specificity= 87.72% [TNF/(FPF+TNF)]		Accuracy= 78.16% (TPF+TNF) Sensitivity= 3.57%[TPF/(TPF+FNF)] Specificity= 99.67%[TNF/(FPF+TNF)]	

Table 5.13 Contingency table for WBSF 14 prediction using all male carcasses

Base line WBSF = 4.5 kg (n=381)		Base line WBSF = 3.4 kg (n=381)	
TPF n=216 56.70%	TNF n=72 18.90%	TPF n=62 16.27%	TNF n=198 51.97%
FNF n=52 13.65%	FPF n=41 10.75%	FNF n=84 22.05%	FPF n=37 9.71%
Accuracy= 75.60% (TPF+TNF) Sensitivity= 80.60% [TPF/(TPF+FNF)] Specificity= 63.74% [TNF/(FPF+TNF)]		Accuracy= 68.24% (TPF+TNF) Sensitivity= 42.46% [TPF/(TPF+FNF)] Specificity= 84.26% [TNF/(FPF+TNF)]	

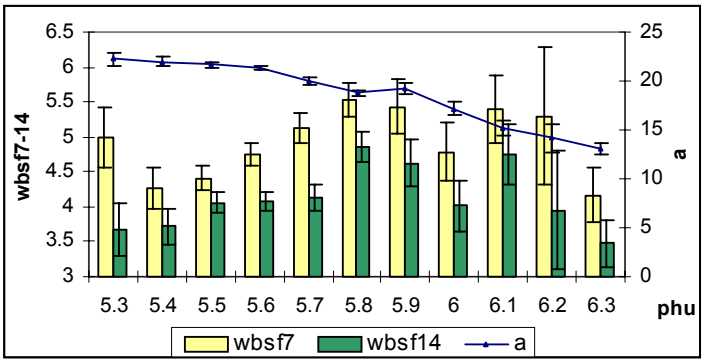

Fig 5.1 WBSF7, WBSF14 and lean a* response with pH_u for all carcasses

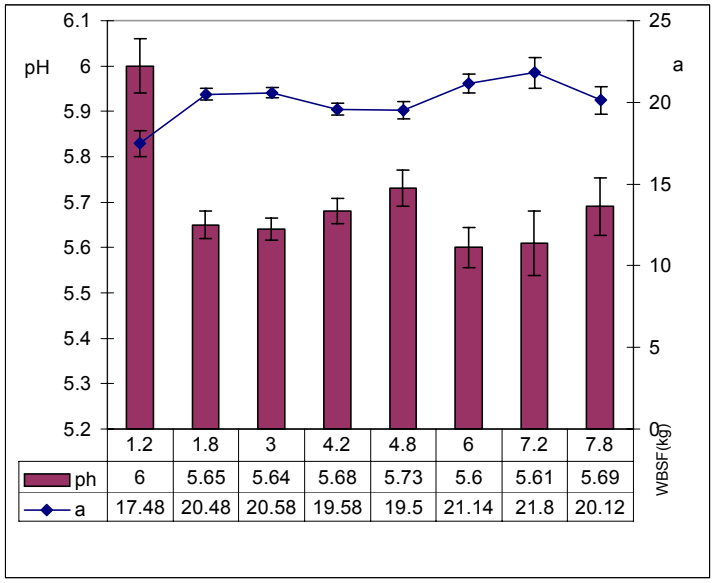

Fig 5.2 Lean a* and pH_u response with WBSF 7 values for all male carcasses

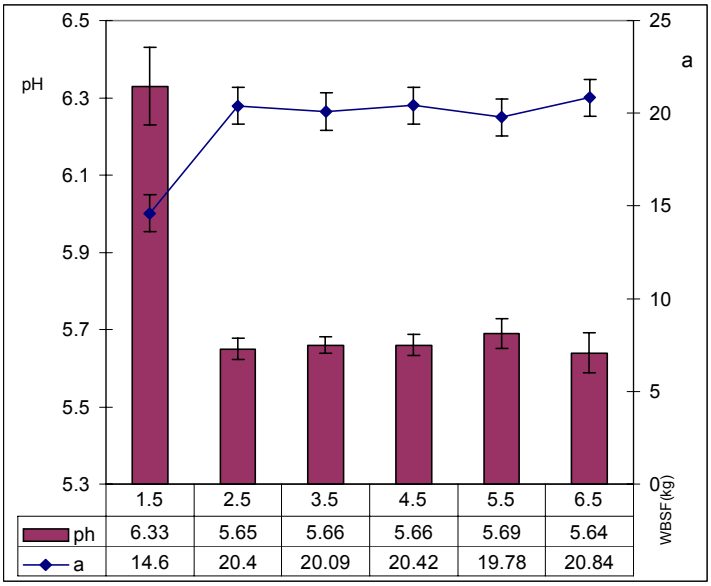

Fig 5.3 Lean a* and pH_u response with WBSF 14 values for all male carcasses

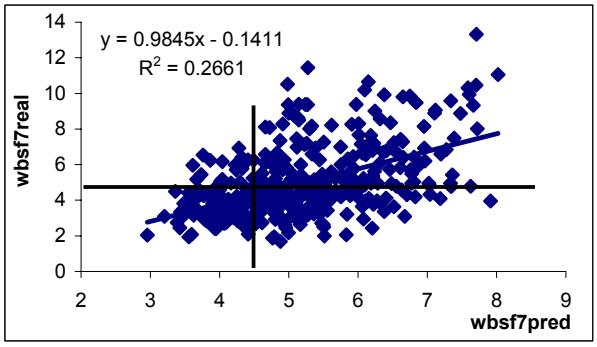

Fig 5.4 Relationship between WBSF 7 and predicted WBSF 7
(the horizontal and vertical lines correspond to WBSF = 4.5 kg)
(Model: dentition, Rea, T_u, pH_u, L*, a*, b*)

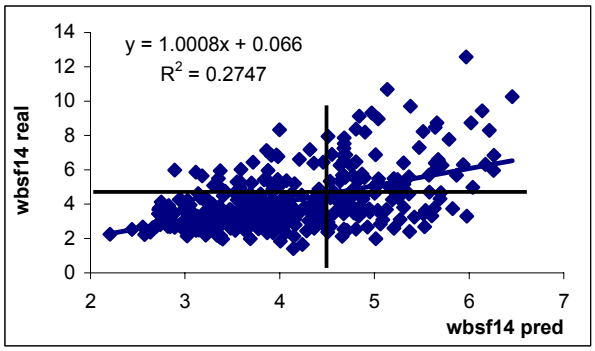

Fig 5.5 Relationship between WBSF 14 and predicted WBSF 14
(the horizontal and vertical lines correspond to WBSF = 4.5 kg)
(Model: dentition, Rea, T_u, pH_u, L*, a*, b*)

CHAPTER 6

CONCLUSIONS

As underlined by many authors, quality improvement must be driven by the consumer expectations and perceptions since they are the ultimate users of the products and food quality is closely related with the concept of acceptability. It is also apparent that the global meat industry will continue to put emphasis on meat quality in terms of palatability and leanness. One way of assuring meat quality in fresh products is implementing quality management systems and on-line process control. The Meat Industry in different countries (United States, New Zealand and Australia) has done several trials to classify carcasses into groups with similar composition and quality. Uruguay as a fresh meat export country (20% of Uruguayan total exports), should be allied to this strategy.

This study was designed as a first attempt in Uruguay to identify effective methods for segregating beef carcasses by tenderness under commercial conditions using postmortem carcass traits. In Experiment 1, a Uruguayan beef female carcass population was characterized in terms of *longissimus* muscle pH, temperature and color in a commercial setting. These variables are well known in their relationship with postmortem processes and beef tenderness. The Uruguayan grading system considers dentition as a variable to differentiate meat quality. However, within young categories (0-4 teeth) this variable can not distinguish carcasses by tenderness differences. Colorimeter readings (lean a*) on beef *longissimus* muscle were shown to be useful predictors of tenderness. There seems to be a threshold lean a* at approximately 20, above which carcasses have lower WBSF values and also lower pH_u. In addition models including lean a*, pH_u, and USDA quality grade were shown in this study to classify beef carcasses into tenderness groups, especially those producing tough meat. The application of USDA quality grading accounted for an additional 3 to 9% of the WBSF 7 and WBSF 14 variation, respectively.

In Experiment 2, a representative population of steers slaughtered in this country was stratified by age, hot carcass weight and backfat thickness. For these animals, objective measures of muscle color, specifically lean a*, were effective in predicting WBSF. Lean a* explained 22 and 16% of WBSF 7 and WBSF 14 variation, by itself. However, analyzing by age category, the prediction of WBSF in 6-8 teeth carcasses was improved through the use of other variables as pH_3 or REA (for WBSF 7 and WBSF 14, respectively). In contrast to the previous experiment the addition of the USDA QG standards to the Uruguayan male carcasses grading did not seem to improve the effectiveness of sorting carcasses into tenderness groups. For this population and from the practical application of systems in the industry, ultimate pH and lean a* measured at ribbing might be useful in sorting beef carcasses likely to yield tough or tender steaks dependent on the defined WBSF threshold.

In Experiment 3, beef male carcass traits, muscle pH, temperature and color were evaluated as potential predictors of tenderness under commercial conditions in two packing plants. Differences in tenderness were found between both packing plants. The best individual variable to explain the variation in tenderness for all selected carcasses was ultimate temperature; however the effect of temperature on the WBSF values was confounded with the different type of cattle (breed and degree of finishing) that were harvested in each packing plant. The addition of other variables such as muscle pH and color and ribeye area increased the accuracy of sorting carcasses into tough or tender groups. The effectiveness of the colorimeter readings to segregate carcasses by tenderness in this experiment was not as useful as the previous ones, although muscle color could be an effective critical control point in the process of ensuring tender beef.

Further investigation should be conducted to determine whether accurate non-invasive methods to predict tenderness in Uruguayan cattle could be developed to identify carcasses likely to produce tender steaks under commercial conditions. Investigation of these methodologies in emerging branded beef programs to improve the final consistency of the product should also be conducted.