



Correlation of Bioelectrical Impedance With Freshness Quality Attributes of Beef *Longissimus Lumborum* Steaks

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Abstract: The quality attributes of beef *longissimus lumborum* during 15 d of retail display were assessed using surface bioelectrical impedance analysis (S-BIA) and internal bioelectrical impedance analysis (I-BIA). Beef loins ($N = 18$) were obtained from 3 commercial processors with 3 postmortem (PM) ages (27, 34, and 37 d). Loins were fabricated into twelve 2.54-cm-thick steaks, subdivided into 6 consecutively cut pairs, and randomly assigned to one of 6 display days (DD): 0, 3, 6, 9, 12, or 15. Steaks were assessed for S-BIA and I-BIA. Three locations were analyzed within each steak: top, middle, and bottom. Microbiological analysis, BIA, pH, instrumental color, proximate composition, and lipid oxidation were measured. There was a location \times PM day \times DD interaction ($P < 0.05$) for *longissimus lumborum* steaks for S-BIA. Among all 3 locations, steaks aged 27 d had higher ($P < 0.05$) S-BIA values on day 9 and 12 than steaks aged 34 and 37 d. There were no location \times PM day \times DD or two-way interactions ($P > 0.05$) for I-BIA. Display day affected ($P < 0.05$) all instrumental color data regardless of PM aging times. Among all PM aging times, steaks aged 27 d were 13% and 7% higher for a^* and b^* , respectively, compared with 34 and 37 d PM. There was a PM day \times DD interaction ($P < 0.05$) for aerobic plate counts (APC). From day 0 and 9 of display, APC of steaks aged 27 d PM were 1 to 2.0 log colony-forming units/cm² lower than steaks aged 34 and 37 d. Quality attributes, including a^* , b^* , APC, and thiobarbituric acid reactive substances, were correlated ($r = 0.70, -0.64, -0.56, \text{ and } 0.69$, respectively) with S-BIA. Overall, BIA values increased on aerobically packaged *longissimus lumborum* steaks and were correlated with various freshness quality parameters.

Key words: beef, bioelectrical impedance, shelf-life attributes, retail

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Introduction

Food waste is an eminent worldwide issue. It has been estimated that approximately one-third of all edible food—or 1.3 billion metric tons—from the beginning of agricultural production fails to reach consumer tables (Gustavsson et al., 2011). A study by Buzby et al. (2014) estimated that 1.2 million metric tons of meat is not being utilized only at the retail level,

which is due to food loss and wasted food products across the United States supply chain. In the US, meat is discounted or discarded due to discoloration, which accounts for 15% of meat loss, leading to industry revenue losses of up to \$1 billion (Smith et al., 2000). As little as 20% surface discoloration is sufficient for consumers to reject meat (Djenane et al., 2001).

Measuring spoilage in meat is of utmost importance to determine freshness in the meat industry.

Bacteria growth and lipid oxidation are two of the major freshness quality traits that affect meat spoilage and can be objectively assessed. Depending upon the environment in the meat packaging, microorganisms at levels of 10^7 to 10^8 log colony-forming units (CFU)/cm² promote the formation of slime and off-odors, leading to spoilage (Ingram and Simonsen, 1980). Furthermore, lipid oxidation of meat is normally evaluated using the thiobarbituric acid reactive substances (TBARS) assay (Witte et al., 1970). Campo et al. (2006) determined that a TBARS value of 2.0 mg malondialdehyde (MDA)/kg caused trained panelists to reject product owing to rancid odor. However, these laboratory-based methods are usually destructive, time-consuming, and training dependent.

The aforementioned drawbacks have set the path for quick and nondestructive methods to assess meat freshness and quality, including the electric nose, near-infrared spectroscopy, hyperspectral imaging technology, torrymeter, and bioelectrical impedance analysis (BIA) using a certified quality reader (CQR). The CQR is a technology that measures impedance as a means to evaluate the freshness of meat by calculating algorithms that assess cellular condition. Bioelectrical impedance, a nondestructive analysis of meat, was first documented in the medical sciences at the beginning of the 1900s (Morse, 1925). Callow (1936) was one of the first meat scientists who studied the electrical characteristics of meat. Some researchers have reported impedance as an effective technology to predict salable yields in beef carcasses (Marchello and Slinger, 1994; Zollinger et al., 2010). In addition, Byrne et al. (2000) studied how electrical impedance affected vacuum-packaged *longissimus dorsi* muscle during postmortem (PM) aging as well as its relationship to other quality traits. Additionally, in ground beef and pork, BIA was found to be an accurate predictor of fat content, especially at smaller grind sizes (Marchello et al., 1999). To the best of our knowledge, little research has been conducted to study the effect of impedance on aerobically packaged *longissimus lumborum* steaks during simulated retail display. Therefore, the effectiveness of BIA to determine the quality attributes of beef and its relationship with meat quality parameters during 15 d of simulated retail display was analyzed.

Materials and Methods

Sample collection

Beef strip loins (Top Choice; $N = 18$; Institutional Meat Purchase Specification #180; USDA Agricultural

Marketing Service, 2014) were obtained from 3 commercial processors, which had different PM age days—27, 34, or 37 d. Loins were cut into 12 steaks of 2.54 cm in thickness and were taken from the anterior to the posterior portion. They were prepared at the Kansas State University (KSU) Meats Laboratory. Steaks were subdivided into 6 consecutively cut pairs and were randomly assigned to one of 6 display days (DD): 0, 3, 6, 9, 12, and 15. Within each pair, one steak was allocated to microbiological analysis and pH measurement. The paired steak was used for BIA, instrumental color assessment, proximate composition, and TBARS. Each steak was placed with the anterior-sliced end facing up on 17S Styrofoam trays (Dyne-a-pak Inc., Laval, QC, Canada) containing Dry-Loc moisture absorbent pads (ac-50; Cryovac, Duncan, SC) and overwrapped with polyvinyl chloride film (23,250 cm³/m²/24 h at 23°C and 0% relative humidity; Borden Packaging and Industrial Products, North Andover, MA).

Display case

Following packaging, steaks were moved to the KSU Color Laboratory and displayed in coffin-style retail cases (model DMF 8; Tyler Refrigeration Corporation, Niles, MI) under fluorescent lights (32 W Del-Warm White 3,000° K; Philips Lighting Co., Somerset, NJ) that emitted a constant 24-h case average intensity of $2,230 \pm 34$ lx. Case temperature was monitored using single channel temperature and humidity sensors (model OM-HL-SP-TH; Omega, Norwalk, CT) and averaged $0.26^\circ\text{C} \pm 0.95^\circ\text{C}$ on steak package surfaces. Cases were defrosted twice daily (morning and evening) at 11°C for 30 min. Steaks were rotated twice a day in the cases from left to right and front to back to account for minor variations in temperature and light intensity within the cases.

Impedance analysis

The freshness of *longissimus lumborum* steaks was assessed using BIA with a CQR (Seafood Analytics CQR, Model Quantum IV, RJL Systems, Clinton Twp., MI) device. Figure 1 depicts the location of the BIA measurements. This technology consists of a 4-electrode device of stainless-steel compression-style electrodes. The outer pair electrodes send a low-frequency electrical current (800 μA , 50 kHz), the voltage capacity of which ranges between 3.75 and 10.60 V. After conductivity is measured, impedance is calculated using the resistance (R) and reactance (X) values that are displayed on the device digital screen. The formula used was impedance in series ($Z = \sqrt{R^2 + X^2}$). The

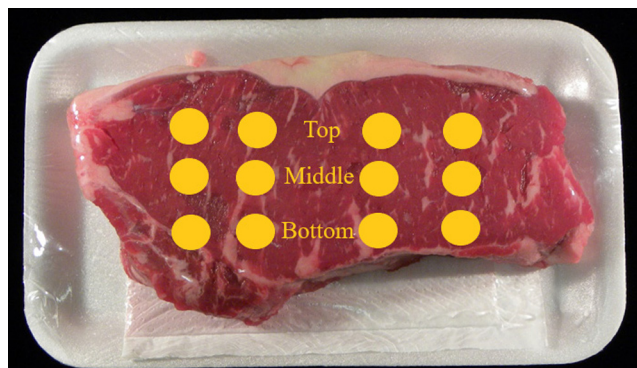


Figure 1. Illustration of anatomical locations of bioelectrical impedance measurements in *longissimus lumborum* steaks.

electrodes were cleaned after every measurement. Three locations within the steak—including top, middle, and bottom, from dorsal to ventral—were evaluated. Three readings were retrieved from each location of the electrodes, and an average was calculated for each steak. The BIA readings were obtained on the surface of the steak by moderately compressing the electrodes up to the middle end (halfway). A template was created to be consistent along the surface BIA (S-BIA) readings. Sample temperature was measured and ranged 0°C to 10°C. Similarly, the internal BIA (I-BIA) of the samples was analyzed using needles inserted at 5 mm. A template was created to be consistent along the S-BIA readings.

Color measurements

Meat color readings for Commission Internationale de l'Éclairage (“International Commission on Illumination”) L^* , a^* , and b^* and reflectance from 400 to 700 nm were instrumentally assessed every sampling day using a HunterLab MiniScan EZ (Illuminant A, 2.54-cm diameter aperture, 10° observer; Model 4500; Reston, VA) according to the methods of Phelps et al. (2014). Readings were taken at 3 steak locations on each day of display, and values were used to calculate an average value for each steak. In addition, steak surface percentages of metmyoglobin and oxymyoglobin were calculated using reflectance values at 473, 525, 572, and 700 nm and using the equations of Krzywicki (1979), as published in the American Meat Science Association Meat Color Measurement Guidelines (American Meat Science Association, 2012). Additionally, a^* and b^* values were used to calculate chroma and hue angle values (American Meat Science Association, 2012).

Microbiological analysis and pH

At each sampling time, steak packages designated for microbial sampling were aseptically opened in the

KSU Microbiology Laboratory, and two 21.6-cm² cores were removed from the steak surface using a sterile scalpel at a depth of 1.5 ± 0.5 mm. Each core was outlined using a sterilized stainless-steel meat coring device. Excised steak samples were placed into sterile plastic bags (Whirl-Pak bags, Nasco, Fort Atkinson, WI) containing 50 mL of sterile 0.1% peptone water (Bacto, Flankin Lakes, NJ). Excised cores were homogenized for 60 s using a stomacher (Model AESAP1064, AES Chemunex, Bruz, France). Serial dilutions of this homogenate were prepared using 9 mL of 0.1% peptone water and plated in duplicate on Petrifilm (3M, St. Paul, MN) to enumerate aerobic plate counts (APC). Samples were incubated and enumerated according to manufacturer instructions. Bacteria populations were calculated, transformed logarithmically, and reported as log CFU/cm². Following microbiological sampling, pH was measured using a calibrated pH probe (Model FC232, Hanna Instruments Inc., Woonsocket, RI) with a pH meter (Model HI 99163, Hanna Instruments Inc.). To determine pH, the probe was inserted in duplicate on the side adjacent to the cores taken for microbial sampling.

Proximate composition

From the paired steak, an additional 50 g was excised, frozen using liquid nitrogen, and homogenized with a blender (Model 33BL79, Waring Products, New Hartford, CT). The homogeneous powder was placed in 11.4 × 22.9-cm plastic labeled Whirl-Pak bags (Fisher Scientific, Fair Lawn, NJ) and stored at –80°C until used for proximate analysis determination and TBARS. The homogeneous powdered samples were analyzed in the KSU Analytical Laboratory for moisture and crude fat content by SMART system 5 (CEM Corporation, Matthews, NC) following AOAC Method (“Official Method PVM-1 MEAT”; AOAC, 2003). Additionally, protein content was analyzed using the LECO FP-2000 Protein/Nitrogen Analyzer (Model 602-600, Leco Corporation, St. Joseph, MI). The combustion method was used, and nitrogen percentage was multiplied by 6.25 to determine the protein content of samples (Leco Corporation, 2011).

Thiobarbituric acid reactive substances

Lipid oxidation during simulated retail display was evaluated using the TBARS assay using procedures as described by Witte et al. (1970). Briefly, 5 g from the homogenous powder was weighed, blended with 45 mL of ice-cold trichloroacetic acid (11%) solution, and homogenized using a Waring blender for 30 s.

One milliliter of filtrate was mixed with 1 mL of 2-thiobarbituric (20 mM) solution. In parallel, a standard curve was created to calculate lipid oxidation using malondialdehyde bis (Millipore Corporation, Billerica, MA). This reaction was carried out in the dark to exclude light. Samples and standards were heated in a 100°C water bath for 10 min and then cooled in room temperature water for 5 min. Following cooling, 0.2 mL of standards and supernatant from each sample were transferred to 96-well plates (in duplicates). Absorbance was read at 532 nm (Eon Microplate Spectrophotometer; BioTek Instruments Inc., Winooski, VT). Values were expressed as milligrams of malonaldehyde per kilogram of muscle.

Statistical analyses

Statistical analysis was executed using the MIXED procedure in SAS/STAT[®] software, version 9.4 (SAS Institute Inc., Cary, NC). The experimental design was a split-plot. For the whole plot, treatment was PM aging time, and the experimental unit was loin. For the subplot, treatment was DD, and the experimental unit was the steak corresponding to loin and DD combination. Impedance measurement was collected at 3 locations of a steak at the surface and internally, leading to the multivariate response.

Data underwent natural-log transformation. Surface impedance and internal impedance were analyzed separately and then analyzed under the linear mixed model. Fixed effects of the model include PM day, DD, location, and all two-way and three-way interactions. Random effect of the model is loin × PM day. Each of the freshness quality attributes was analyzed, separately, under the linear mixed model with fixed effects of PM day, DD, and PM day × DD. The random effect of the model was loin × PM day. Least-squares mean and its standard errors—back-transformed to the original scale when applicable—were reported for fixed effects. The adjustment for multiplicity was carried out using Tukey's method at the 0.05 significance level. The CORR procedure of SAS was used to calculate the correlation of S-BIA and I-BIA (on the natural-log scale). Impedance averaged across the 3 locations and DD was used.

Results

Bioelectrical impedance

There was a location × PM day × DD interaction ($P < 0.05$) for *longissimus lumborum* steaks when

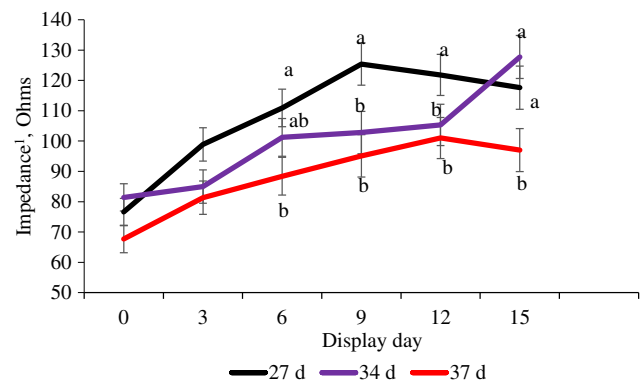


Figure 2. Interaction for top-bioelectrical impedance values of beef *longissimus lumborum* steaks aged 27, 34, and 37 d and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$. ^{a,b}Means with different superscripts differ ($P < 0.05$). ¹Back-transformed LSMEANS.

assessed for S-BIA. Because all locations acted independent of one another, PM day × DD interactions were analyzed by steak location. Figure 2 shows the interaction for Top-S-BIA. From day 0 to day 3 of display, Top-S-BIA values were similar ($P > 0.05$) for all PM aging times. On day 6, steaks aged 27 d were similar to steaks aged 34 d but 26% higher than those aged 37 d. Moreover, steaks aged 34 d and those aged 37 d were similar ($P > 0.05$). On day 9, steaks aged 27 d were 19% and 24% higher ($P < 0.05$) than steaks aged 34 and 37 d, respectively. Top-S-BIA values of steaks aged 27 d were higher ($P < 0.05$) than steaks aged 34 and 37 d on day 12. However, on day 15, steaks aged 27 d and those aged 34 d were similar ($P > 0.05$) but 18% higher than steaks aged 37 d. The interaction for Middle-S-BIA is presented in Figure 3. From day 0 to day 3 of display, Middle-S-BIA values were similar ($P > 0.05$) for all PM aging times. On day 6, steaks aged 27 d were similar ($P > 0.05$) to steaks aged 34 d but 17% higher ($P < 0.05$) than those aged 37 d. The Middle-S-BIA values of steaks aged 34 and 37 d were similar ($P > 0.05$) and 24% and 12% lower ($P < 0.05$)

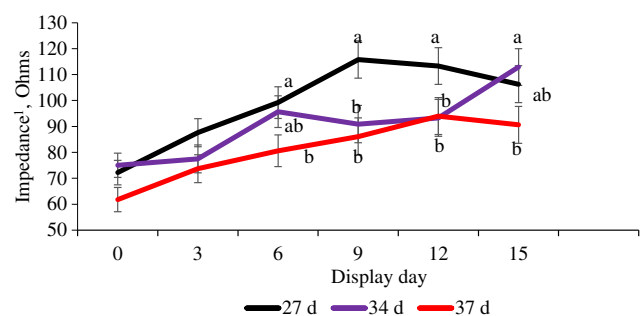


Figure 3. Interaction for middle-bioelectrical impedance values of beef *longissimus lumborum* steaks aged 27, 34, and 37 d and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$. ^{a,b}Means with different superscripts differ ($P < 0.05$). ¹Back-transformed LSMEANS.

than those of steaks aged for 27 d on days 9 and 12, respectively. On day 15, steaks aged 34 d were similar ($P > 0.05$) to steaks aged 27 d but 14% higher than steaks aged 37 d. In addition, steaks aged 27 and those aged 37 d were similar ($P > 0.05$). Interaction for Bottom-S-BIA can be found in Figure 4. From day 0 to day 6 of display, all PM aging times were similar ($P > 0.05$). On days 9 and 12, the Bottom-S-BIA values of steaks aged 27 d were 24% and 15% greater ($P < 0.05$) than steaks aged 34 and 37 d, respectively. Furthermore, on day 15 of retail display, Bottom-S-BIA values of steaks aged 27 and 34 d were similar ($P > 0.05$) and were 21% higher ($P < 0.05$) than steaks aged 37 d. Additionally, location, PM day, and DD effects were found ($P < 0.05$). There was no three-way or two-way interaction ($P > 0.05$; Table 1) for

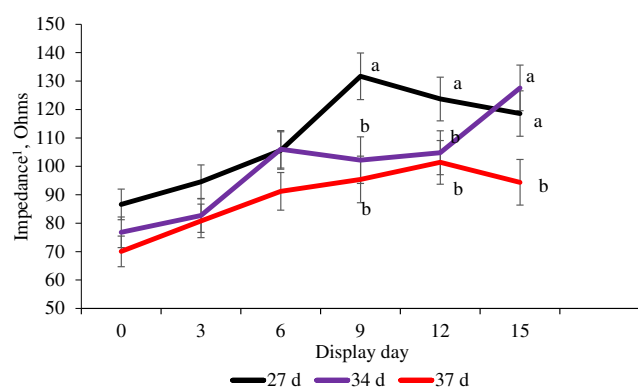


Figure 4. Interaction for bottom-bioelectrical impedance values of beef *longissimus lumborum* steaks aged 27, 34, and 37 d and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$. ^{a,b}Means with different superscripts differ ($P < 0.05$). ¹Back-transformed LSMEANS.

longissimus lumborum steaks for I-BIA, but a main effect due to location, PM day, and DD was found ($P < 0.05$). The middle portion had lower ($P < 0.05$) I-BIA values than the top and bottom portion. Because of a technical problem with the I-BIA probe, data were removed on day 0 for the middle portion.

Instrumental color assessment

There were no PM day \times DD interactions ($P > 0.05$) for a^* and b^* values; however, there was an interaction ($P < 0.05$; Figure 5) for L^* values. On day 0, steaks aged 34 d and those aged 37 d were similar ($P > 0.05$); however, these 2 PM aging times were 6% darker ($P < 0.05$) compared with steaks aged 27 d. On day 3 of display, L^* scores from all PM aging times were not different ($P > 0.05$). On day 6, steaks aged 27 d and those aged 34 d were similar ($P > 0.05$) but 6% lighter ($P < 0.05$) than those steaks of loins aged 37 d. From day 9 through day 15 of display, L^* scores did not differ ($P > 0.05$) among all PM aging treatments. PM aging time had no effect ($P > 0.05$) on L^* . As expected, DD affected ($P < 0.05$; Table 2) redness and blueness. Furthermore, compared with steaks aged 34 and 37 d PM, steaks aged 27 d were more red (greater a^* values; $P < 0.05$; Table 3) and yellow (greater b^* values; $P < 0.05$) by 10% and 5% ($P < 0.05$), respectively. No interactions were observed for surface metmyoglobin, deoxymyoglobin, or oxymyoglobin ($P > 0.05$). DD affected ($P < 0.05$; Table 4) metmyoglobin, deoxymyoglobin, and oxymyoglobin accumulation. By day 0 and through 6 d of display, the surface metmyoglobin increased ($P < 0.05$); however,

Table 1. Internal impedance means¹ of beef *longissimus lumborum* steaks aged 27, 34, and 37 d and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$

Location	PM ²	Display day											
		0		3		6		9		12		15	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Top	27 d	88.0	4.0	105.3	4.8	130.3	5.9	128.5	5.8	120.0	5.4	122.0	5.5
	34 d	81.0	3.7	91.5	4.1	112.3	5.1	108.4	4.9	113.5	5.1	124.4	5.6
Middle	37 d	74.3	3.4	85.3	3.9	102.6	4.8	103.2	4.7	101.7	4.6	106.3	4.8
	27 d	-	-	91.0	4.5	103.6	5.2	111.4	5.5	107.3	5.3	104.8	5.2
	34 d	-	-	79.9	4.0	95.4	4.8	91.1	4.5	95.0	4.7	114.9	5.7
Bottom	37 d	-	-	74.6	3.7	88.6	4.5	88.0	4.5	93.2	4.7	90.2	4.6
	27 d	87.1	4.5	101.8	5.3	114.6	5.9	124.9	6.5	126.3	6.5	128.7	6.7
	34 d	82.1	4.3	89.3	4.6	109.1	5.7	103.1	5.3	109.4	5.7	122.3	6.3
	37 d	74.1	3.8	82.1	4.3	97.0	5.0	97.0	5.0	104.7	5.4	99.6	5.2

¹Back-transformed LSMEANS.

²Postmortem (PM) aging time.

Location \times PM \times display day (DD) interaction ($P > 0.05$). Location \times PM interaction ($P > 0.05$). Location \times DD interaction ($P > 0.05$). Location main effect ($P < 0.05$). PM aging time main effect ($P < 0.05$). DD main effect ($P < 0.05$).

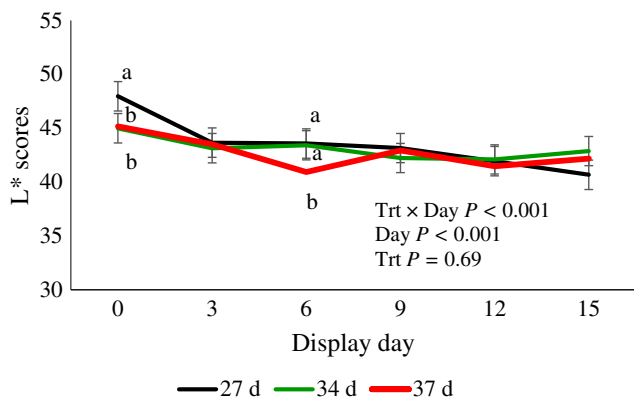


Figure 5. Interaction for lightness scores of beef *longissimus lumborum* steaks aged 27, 34, and 37 d and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$. ^{a,b}Means with different superscripts differ ($P < 0.05$).

after day 9, the surface metmyoglobin remained constant ($P > 0.05$). Additionally, no PM day effect ($P > 0.05$; Table 5) was found on all surface measurements. No PM day \times DD interactions ($P > 0.05$) were found for hue angle and chroma values. Hue angle values increased ($P < 0.05$) over the 15-d retail display, indicating a less red over time. A decrease ($P < 0.05$) in

chroma values was observed, following a similar pattern as redness values. There were no differences ($P > 0.05$) in hue angle values among all PM aging times. Chroma was 7% greater ($P < 0.05$) in steaks aged 27 d PM than steaks aged 34 and 37 d PM, indicating a more intense red in steaks with less PM.

Aerobic plate counts

There was a PM day \times DD interaction ($P < 0.05$; Figure 6) for APC populations. Initially, steaks aged 27 d had the lowest ($P < 0.05$) APC populations with 2.3 log CFU/cm² in comparison to steaks aged 34 and 37 d, which had a similar ($P > 0.05$) APC growth with 4.3 and 4.5 log CFU/cm², respectively. Aerobic plate counts from steaks aged 27 d remained lower ($P < 0.05$) compared with those from the 2 other steak age groups until 12 and 15 DD, when they were no longer different and were >6 log CFU/cm². Furthermore, steaks aged 37 d had a higher ($P < 0.05$) prevalence of APC populations than steaks aged 34 d only on day 3 and day 6. Additionally, a PM day and DD effect ($P < 0.05$) were found for APC populations.

Table 2. Least-squares means for the display day effect for redness and yellowness of beef *longissimus lumborum* steaks aged three different time periods and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$

	Display day						SEM	P value
	0	3	6	9	12	15		
a*	33.05 ^a	29.08 ^b	21.33 ^c	13.24 ^d	11.50 ^{de}	10.91 ^f	1.01	< 0.01
b*	25.80 ^a	23.54 ^b	20.09 ^c	18.04 ^d	17.33 ^d	16.98 ^d	0.64	< 0.01

^{a-f}Means with different superscripts within a row differ ($P < 0.05$).

Table 3. Least-squares means for the postmortem age effect for redness and yellowness of beef *longissimus lumborum* aged three different time periods and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$

	Postmortem age			SEM	P value
	27 d	34 d	37 d		
a*	21.45 ^a	19.23 ^b	18.88 ^b	0.77	< 0.01
b*	21.10 ^a	20.12 ^b	19.66 ^b	0.46	0.02

^{a,b}Means with different superscripts within a row differ ($P < 0.05$).

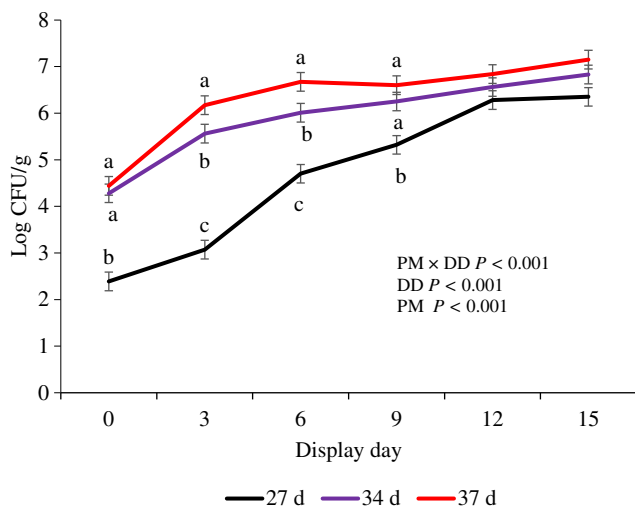
Table 4. Least-squares means for the display day effect for surface discoloration of beef *longissimus lumborum* steaks aged three different time periods and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$

	Display day						SEM	P value
	0	3	6	9	12	15		
Metmyoglobin	18.64 ^d	25.44 ^c	39.60 ^b	60.02 ^a	60.17 ^a	58.84 ^a	2.35	< 0.01
Deoxymyoglobin	3.00 ^{ab}	5.85 ^a	6.35 ^a	5.29 ^a	3.62 ^{ab}	0.76 ^b	2.17	0.11
Oxymyoglobin	78.35 ^a	68.71 ^b	54.15 ^c	34.68 ^c	36.20 ^{de}	40.38 ^d	3.37	< 0.01

^{a,b}Means with different superscripts within a row differ ($P < 0.05$).

Table 5. Least-squares means for the postmortem age effect for surface discoloration of beef *longissimus lumborum* steaks displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$

	Postmortem age			SEM	P value
	27 d	34 d	37 d		
Metmyoglobin	41.89	45.31	44.15	2.68	0.45
Deoxymyoglobin	4.51	3.04	4.89	2.86	0.79
Oxymyoglobin	53.59	51.64	51.00	1.80	0.32

**Figure 6.** Interaction for APC populations of beef *longissimus lumborum* steaks aged 27, 34, and 37 d and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$. ^{a-c}Means with different superscripts differ ($P < 0.05$). APC = aerobic plate counts; CFU = colony-forming units; DD = display days; PM = postmortem age.

TBARS

No PM day \times DD interaction or PM effect ($P > 0.05$) was found for TBARS; however, there was a DD effect ($P < 0.05$; Table 4). From day 0 to day 3, TBARS values were similar ($P > 0.05$) with 0.14 and 0.19 mg MDA/kg; however, lipid oxidation increased to 0.38 mg MDA/kg on day 6. By day 9 and 12,

TBARS values remained constant ($P > 0.05$). On day 15 of display, lipid oxidation was the highest ($P < 0.05$) among all DD with 0.79 mg MDA/kg.

Proximate composition and pH

There was no PM day \times DD interaction ($P > 0.05$) or PM day effect ($P > 0.05$) for protein, fat, and moisture content. A DD effect ($P < 0.05$; Table 6) was found for protein and moisture content. Although significant, the variation during retail display was around 1%. Steaks' protein content was similar ($P > 0.05$) at all DD, except from day 6 to day 9, when protein content decreased ($P < 0.05$) by 2%. However, it was observed that DD affected protein and moisture content ($P < 0.05$). In addition, no PM time effect ($P > 0.05$; Table 7) was found on protein, moisture, and fat content. A PM day \times DD interaction was observed ($P < 0.05$; Figure 7) for pH. On day 0, 6, 9, 12, and 15 of display, pH was similar ($P > 0.05$) among all PM aging times. On day 3, however, steaks aged 34 d had a higher ($P < 0.05$) pH than steaks aged 37 d but were similar ($P > 0.05$) to steaks of loins aged 27 d. Overall, the pH variation was limited and ranged from 5.48 to 5.65.

Correlations

Moderate negative correlations ($P < 0.01$; $r = -0.56$; Table 8) occurred between S-BIA values and instrumental color measurements, including a^* and b^* . No correlations ($P > 0.05$) were found for L^* values for steaks aged 34 d. Although no correlation ($P > 0.05$) was found between S-BIA and moisture content for steaks aged 27 and 37 d, steaks aged 34 d were negatively correlated ($P < 0.01$; $r = -0.67$). No correlation ($P > 0.05$) between S-BIA values and fat content was found for steaks aged 27 and 37 d. Aerobic plate counts and TBARS ($P < 0.01$; $r = 0.70$) were correlated with S-BIA values for all PM aging times. I-BIA was correlated ($P < 0.05$; Table 9) with all the parameters tested except

Table 6. Least-squares means for the display day effect for proximate composition of beef *longissimus lumborum* steaks aged three different time periods and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$

	Display day						SEM	P value
	0	3	6	9	12	15		
Protein	22.96 ^a	22.74 ^{ab}	22.73 ^{ab}	22.35 ^b	22.69 ^{ab}	23.02 ^a	0.20	0.03
Fat	5.02	4.41	5.34	5.48	5.35	5.60	0.49	0.19
Moisture	70.57 ^b	71.52 ^a	70.60 ^b	70.40 ^b	70.43 ^b	69.69 ^b	0.45	< 0.01
¹ TBARS	0.14 ^d	0.19 ^d	0.38 ^c	0.65 ^b	0.60 ^b	0.79 ^a	0.049	< 0.01

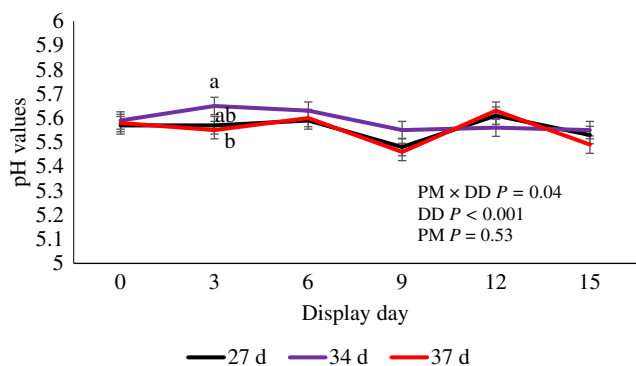
^{a,b}Means with different superscripts within a row differ ($P < 0.05$).

¹TBARS = thiobarbituric acid reactive substances.

Table 7. Least-squares means for the postmortem age effect for proximate composition of beef *longissimus lumborum* steaks displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$

	Postmortem age			SEM	P value
	27 d	34 d	37 d		
Protein	22.87	22.59	22.77	0.25	0.55
Fat	5.44	5.60	4.56	0.57	0.17
Moisture	70.10	70.23	71.27	0.56	0.11
¹ TBARS	0.42	0.50	0.46	0.06	0.40

¹TBARS = thiobarbituric acid reactive substances.

**Figure 7.** Interaction for pH values of beef *longissimus lumborum* steaks aged 27, 34, and 37 d and displayed for 15 d under fluorescent lighting at $0.26^{\circ}\text{C} \pm 0.95^{\circ}\text{C}$. ^{a,b}Means with different superscripts differ ($P < 0.05$). DD = display days; PM = postmortem age.

for color lightness (L^*) and protein content for PM aging of 27 and 37 d.

Discussion

Historically, numerous groups have studied BIA to predict or indicate various quality attributes in beef and other species, including pork, poultry, and fish (Marchello and Slanger, 1994; Marchello et al., 1999; Cox et al., 2011). In addition, few studies have

evaluated meat freshness as means to predict the shelf life of meat using electrical properties (Sujiwo et al., 2019). In an attempt to measure freshness of *longissimus lumborum* steaks, Sujiwo et al. (2019) used a torrymeter tool to measure the dielectrical properties of fresh meat and reported a decrease of torrymeter values on aerobically packaged *longissimus lumborum* steaks during an 18-d retail display. The torrymeter had an integrated system that utilizes a band pass filter at a wide range of frequencies. As a result, this provides a greater chance to detect the correct frequency at each sampling time. On the other hand, the CQR equipment used in this study utilizes a single frequency (50 Hz), thus limiting its potential to assess the freshness of beef.

The PM effect of electrical impedance on *longissimus lumborum* steaks was also evaluated. When the PM time increased, S-BIA values decreased during retail display in the current study. Steaks from loins with a longer PM aging time had lower S-BIA values during retail display compared with those steaks from loins with shorter aging time. These results are consistent with those from Byrne et al. (2000). They measured the internal impedance in muscle, and their results indicated that as PM aging increased, I-BIA values decreased in vacuum-packaged *longissimus dorsi* muscle. The commercial application for measuring internal impedance may pose a food safety concern because there is a risk of translocating bacteria into the meat, compromising the internal condition of the product. In a previous study, it was demonstrated that impedance and conductivity are good indicators of membrane integrity in pork (Kleibel et al., 1983). These results follow the pattern of other studies indicating a change in BIA values of meat during PM aging. Recently, Chao et al. (2020) reported an increase in pork membrane degradation after PM aging. This may help explain why higher BIA values are associated with increased PM aging. Additionally, dorsal (top) and ventral (bottom) portions of the steak had greater BIA values (data not shown) compared with the middle portion. Results

Table 8. Correlation coefficients between beef *longissimus lumborum* steak electrical measurements collected using S-BIA and redness, APC, TBARS, and moisture content

PM	L^*	a^*	b^*	Protein	Moisture	Fat	APC	pH	TBARS
27 d	-0.56**	-0.66***	-0.56***	-0.12	-0.22	0.03	0.70***	-0.23	0.82***
34 d	-0.15	-0.64***	-0.69***	-0.06	-0.67***	0.45***	0.72***	-0.30*	0.69***
37 d	-0.43**	-0.70***	-0.65***	-0.13	0.20	0.27*	0.72***	0.18	0.72***

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

APC = aerobic plate count; PM = postmortem age; S-BIA = surface bioelectrical impedance analysis; TBARS = thiobarbituric acid reactive substances.

Table 9. Correlation coefficients between beef *longissimus lumborum* steak electrical measurements collected using I-BIA and redness, APC, TBARS, and moisture content

PM	L^*	a^*	b^*	Protein	Moisture	Fat	APC	pH	TBARS
27 d	-0.10	-0.56***	-0.44**	-0.02	-0.68***	0.57***	0.58***	-0.29*	0.63***
34 d	0.06	-0.64***	-0.69***	-0.29*	-0.73***	0.58***	0.85***	-0.24*	0.67***
37 d	-0.25	-0.71***	-0.69***	0.16	-0.63***	0.40**	0.87***	0.45**	0.62***

* $P < 0.05$.** $P < 0.01$.*** $P < 0.001$.

APC = aerobic plate count; I-BIA = internal bioelectrical impedance analysis; PM = postmortem age; TBARS = thiobarbituric acid reactive substances.

previously reported by Goihl et al. (1992) have demonstrated the presence of a fat and moisture gradient difference between dorsal and ventral locations in fresh *longissimus lumborum* steaks which is likely to influence the impedance measurements. Time in display case affected S-BIA values. Regardless of PM aging times, from day 0 through day 9, a linear increase of the impedance measurement was observed. After day 9, S-BIA values had more variation and were inconsistent. As meat ages, there is an increase in proteolysis (Huff-Lonergan and Lonergan, 2005), resulting in poor water-holding capacity and possibly affecting BIA values.

Color is the most important quality attribute for consumers as it influences their purchasing decisions (Mancini and Hunt, 2005). It has been well established that increased PM aging time decreased color stability (Tang et al., 2005; Lindahl, 2011). Research has reported that aerobically packaged *longissimus dorsi* steaks' color stability was negatively affected when PM aging time increased (Lindahl, 2011). In the current study, an initial increase in L^* was observed for steaks aged 27 d compared with steaks aged 34 and 37 d. These results are in contrast with those from Dietz (2014), as he found that *gluteus medius* steaks with increased PM aging time had higher initial L^* compared with steaks with shorter PM aging time. Steaks aged 27 d were more red and yellow and had greater chroma values than steaks from loins aged 34 and 37 d. Our data on surface redness, yellowness, and chroma follow other reported literature (Colle et al., 2015; English et al., 2016; Abraham et al., 2017), which indicated that displaying steaks from loins with increased PM aging may lead to a faster red and yellow color loss. This study showed no differences among all PM aging times for hue angle values. However, Ramanathan et al. (2019) found that steaks from beef strip loins with less PM aging time had lower hue angle values. As expected, a decrease in surface oxymyoglobin and a simultaneous increase in metmyoglobin percentage was observed as display time increased. Phelps et al.

(2016) reported similar results in *longissimus lumborum* steaks during a 7-d retail display.

Consumers often misunderstand meat discoloration and conclude that the product has reached the end of its usable shelf life. However, color shelf life and bacterial shelf life of meat are not always following one another, as changes in fresh meat color during retail display is a natural process and does not mean that a product is spoiled (USDA-FSIS, 2013). Spoilage in meat occurs when organoleptic properties are lost and bacterial degradation of amino acids triggers slime formation and off-flavor development on the meat surface (Gill, 1997). The spoilage process is undergone when bacteria growth exceeds 10^7 log CFU/cm² (Ingram and Simonsen, 1980; Gill, 1982). Overall, APC populations were relatively lower in steaks from loins aged 27 d—which ranged from 2.39 to 6.35 log CFU/cm² throughout the retail display—than their counterparts aged 34 and 37 d. Following the aforementioned recommendations, steaks aged 27 and 34 d had a shelf life of 15 d, respectively, and steaks aged 37 d had 12 d of shelf life under the conditions used in this study.

At the end of the 15 d of display, steaks achieved a TBARS value of 0.79 mg MDA/kg. Similar results were found in *longissimus thoracis* steaks, in which TBARS reached 0.86 mg MDA/kg at the end of 18-d retail display (Sujiwo et al., 2019). A consumer panel determined that 2.0 mg MDA/kg was sufficient to detect oxidation in beef (Greene and Cumuze, 1981). After day 9 of display, TBARS values were equal to or greater than 0.6 mg MDA/kg, indicating that these steaks had higher lipid oxidation but were nonetheless below the oxidation detection threshold.

It has been determined that impedance values may change due to proteolysis when the membrane of muscle tissue is affected during post-rigor (Reichert, 1996). The highest correlation was shown between BIA and a^* , TBARS, and APC, which were negatively correlated for all PM aging times, reflecting an increase in BIA and a decrease in these quality attributes.

Sujiwo et al. (2019) conducted a retail display study using *longissimus thoracis* steaks and found similar results, in which APC, a^* , and b^* were highly correlated with torrymeter values. Torrymeter measures the phase angle with a wide range of frequencies. Sujiwo et al. (2019) used steaks with 24-h-PM aging time, providing the opportunity for protein degradation to occur; therefore, a more consistent decrease was observed. Overall, these results indicate that BIA may be considered as a tool to assess correlations with freshness quality attributes, including redness, APC, and TBARS in beef during retail display. Additionally, the measurement of pH has historically been used to evaluate the freshness of carcass and meat quality (Korkeala et al., 1986). Although weak correlations were found between pH and BIA in this study, other literature has previously reported a moderate to high correlation ($r = 0.91$) between these 2 measurements (Sujiwo et al., 2019). In this study, pH variation is so little that it is not surprising that no correlation was found.

Conclusions

Overall, I-BIA and S-BIA values increased on aerobically packaged *longissimus lumborum* steaks and were correlated with various quality parameters, including redness, yellowness, APC, and TBARS. However, the needles used in the I-BIA method are invasive and may translocate bacteria into the muscle; therefore, the use of the S-BIA method is recommended. Regardless of BIA method, lower BIA values serve as a tool to identify steaks from the *longissimus lumborum* that have undergone at least 34 d of PM aging. Further research should be conducted to study the effect of S-BIA on protein degradation of structural proteins.

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