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Postmortem changes in muscle electrical properties of bovine *M. longissimus dorsi* and their relationship to meat quality attributes and pH fall

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Abstract

Heifers ($n = 47$) were slaughtered and hung conventionally in an industrial meat plant. Electrical impedance (Py) and conductivity (EC) were studied for their ability to indicate or predict selected meat quality attributes i.e. Warner–Bratzler shear force (WBSF), sensory tenderness, texture, flavour and acceptability, water holding capacity (WHC) and colour. pH, electrical impedance (meat check) and electrical conductivity (pork quality meter) measurements were taken at hourly intervals up to 8 h and again at 1 and 2 days postmortem. Electrical measurements were taken again at 7 and 14 days postmortem. Freshly cut steaks (2.5 cm thick) were taken from the *longissimus dorsi* (LD) muscle at 2, 7 and 14 days postmortem, vacuum-packaged in plastic bags and stored at −20°C for WBSF and sensory analysis. Freshly cut steaks were used for WHC and colour measurements. During the development of rigor and over the ageing period, electrical changes occur in muscle tissue. Electrical measurements were found to change significantly between 1 and 14 days postmortem and when measured over the ageing period (at 2, 7 and 14 days postmortem) were significantly correlated to WBSF, sensory tenderness and Hunter '*a*' and '*b*' values ($r = \pm 0.56$–± 0.68, $p < 0.001$) and weakly to moderately correlated to other sensory attributes ($r = \pm 0.31$–0.58, $p < 0.001$) measured at the same times postmortem; thus showing potential for these rapid physical measurements as indicators of meat quality if both electrical measurements and quality attributes are measured at the same times postmortem and correlations are calculated over the ageing period. However, electrical measurements taken at specific times at the early postmortem period (i.e. at 1 or 2 days) showed only a few weak relationships with meat quality attributes measured at later times postmortem (i.e. 7 or 14 days) demonstrating that early postmortem electrical measurements are not suitable for the prediction of ultimate meat quality. Py values taken between 7 h and 7 days postmortem were significantly correlated with all pH measurements with the exception of 1 day values. Two day Py measurements showed the highest correlations ($r = 0.45$–0.62, $p < 0.01$–0.001) with pH. EC was also found to be moderately correlated with pH although correlations were slightly lower than those obtained for Py. Highest correlations ($r = 0.47$–0.59, $p < 0.01$) were obtained for 7 h values.

1. Introduction

Consumers tend to evaluate meat quality on the basis of the tenderness, juiciness and flavour of the cooked meat (Carpenter, 1966). Meat colour is another important quality attribute as it largely determines the consumer's initial decision to buy beef (Hood & Riordan, 1973). However, the acceptability of beef after purchase is determined almost exclusively by the satisfaction derived from its consumption (Jeremiah, Tong & Gibson 1991). Texture or tenderness is the predominant quality determinant and is probably the most important organoleptic characteristic of red meat (Koohmaraie, 1988). Variability in the quality of meat has long been a consumer concern. In 1982, Jeremiah concluded that the most common cause of unacceptability in beef was toughness (Jeremiah, 1982). More recent surveys have also shown that consumers have difficulty in selecting beef because they are unsure of the quality, particularly the tenderness (Dransfield, 1994). There are numerous reports on methods for measurement of meat tenderness (Cross, West & Dutson, 1980; Fritz, Mitchell,

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Marsh & Greaser, 1993; Moller, Vastergaard & Wismer-Pedersen, 1973; Purchas, 1990; Szezniak & Torgeson, 1965; Warner, 1928). However, most methods are destructive and time-consuming or they use predictors which are not highly correlated to the actual tenderness. There is, therefore, considerable need to find efficient, non-destructive methods for assessing meat tenderness. These could improve the reliability of meat grading systems and quality control systems to maintain consumer demand for beef.

Muscle has certain electrical characteristics such as impedance and conductivity which change with time postmortem. The electrical conductivity of a material is a measure of its ability to conduct electricity. The SI unit for conductivity is the siemen (S). In terms of electric circuit analysis, electrical impedance is generally defined as the total opposition to the flow of an alternating current at a given frequency (Honda, 1989). That is the combined opposition to the flow of current offered by the resistive, capacitive and inductive components. For meat, however, impedance may be visualised as the hypotenuse of a triangle whose base is resistance and whose height is capacitance (Swatland, 1995). While the SI unit of impedance is the ohm (Ω), the measuring value (Py) of the Meatcheck instrument used in this study is a dimensionless unit ranging from 0 to 100. A Py value of zero represents intact cells, a Py value of 100 represents watery medium. Both impedance and conductivity measurements are indicators of membrane integrity (Kleibel, Pfutzner & Krause, (1983) and change when damage to differing degrees occurs to the membrane system of the muscle tissue during postmortem glycolysis (Reichert, 1996). Changes in membrane permeability enhance the ion transport i.e. the flow of current through a muscle. Therefore, enhanced conductivity or impedance is an indirect measurement of enhanced drip loss or muscle softness which is a consequence of leaky membrane structures which allow fluids to move between the intracellular and extracellular spaces (Pliquett, Pliquett & Robekamp, 1990). Also, since water is held in the spaces between the thick and thin filaments (Offer et al., 1989), any changes in the content and distribution of water within the meat originating from changes in this spacing will undoubtedly have an influence on muscle electrical properties.

The idea of using an electrical probe to investigate the quality of meat within a carcass, dates back to the late 1930s in England, where Callow (1936) noted an increase in the number of DFD (dark, firm and dry) pork carcasses when rail transport and central abattoirs first replaced the slaughtering of pigs near the farm. Since then, various workers have related these electrical characteristics to meat quality but it is only recently, through progress in digital and optical electronics (Swatland, 1994), that instruments have become commercially available which exploit these relationships to predict quality on the slaughterline (Bendall & Swatland, 1988).

Meat quality is influenced to a large extent by the rate of pH decline in the muscles after slaughter and by the ultimate pH (Marsh, Ringkob, Russel, Swartz & Pagel, 1988; O'Halloran, Troy & Buckley, 1997; Sales & Mellett, 1996). Marsh, Ringkob, Russel, Swartz and Pagel (1987) stated that tenderness was highest when glycolysis proceeded at a rate which resulted in a pH at 3 h (pH_3) of 6.1 and that tenderness was appreciably lower on either side of this value. In 1988, these authors concluded that unaged steaks with pH_3 of 6 were as tender as fully aged steaks which had attained very low pH_3 values. Similarly, Pike, Ringkob, Beekman, Koh and Gerthoffer (1993) reported that optimum tenderness was produced by stimulating carrcasses or sides to yield a pH_3 of 6. The relationship between ultimate pH (pH_u) and meat tenderisation has also been studied. Fjelkner-Modig and Ruderus (1983) reported a quadratic relationship between pH_u and tenderness of muscle tissue. The high pH_u meat had a higher initial tenderness than normal and intermediate, but a smaller increase in tenderness was noted during storage. Purchas (1990) reported a curvelinear relationship with meat tenderness and pH, with a minimum tenderness of LD at a pH_u of approximately 6.

At present, pH is one of the few methods of assessing meat quality in an industrial meat plant. Since there is often a high degree of experimental error associated with the use of glass pH electrodes in meat (Swatland, 1985), making pH difficult to measure on the slaughterline, another more sensitive parameter which is related to the pH decline would be of value in assessing and predicting meat quality at the early postmortem period. During rigor development, complex electrical changes occur in muscle tissue which, if correlated with muscle pH decline may be of value in the assessment of meat quality. Use of electrical probes have many inherent advantages over glass pH electrodes. Measurement speed is faster and an internal memory for data storage allows for complete automation. Electrical probes are more robust and less destructive than pH probes. They are also water resistant and easier to clean and use and they do not require constant recalibration as do pH probes and they offer no health hazards.

2. Materials and methods

2.1. Cattle slaughtering and sample preparation

Heifers ($n=47$) of similar age, size and grade, were selected in an industrial meat plant. Slaughtering was effected by stunning using a captive-bolt pistol and exsanguination, after which each carcass was conventionally dressed and split into two sides. The right hand side *longissimus dorsi* (LD) muscles which were used for the purposes of this experiment were then chilled at 12–13°C for 10 – 11 h, followed by storage in a 0°C chill until 24 h postmortem at which time the LD muscles were excised. The rate of pH and temperature fall was monitored up to 1 and 2 days, respectively. Electrical measurements were monitored up to 14 days postmortem. Freshly cut samples (2.5 cm thick) were taken at 2, 7 and 14 days postmortem, vacuum-packaged in plastic bags and stored at −20°C for Warner–Bratzler shear force (WBSF), sensory analysis and cook loss determination. Drip loss and colour measurement were carried out on freshly cut steaks.

2.2. pH and temperature measurements

pH was measured using a portable pH meter (Orion) and combined electrode which was inserted approximately two inches into the LD muscle between the 9th and 13th ribs at hourly intervals up to 8 h and again at 1 and 2 days postmortem. New cuts were made in the meat for each measurement. The temperature of the LD muscles was measured with a data logger (Grant Squirrel series 1250) at 15 min intervals up to 24 h postmortem, by inserting temperature probes approximately two inches into the LD muscle immediately anterior to the 9th rib (May, Dolezal, Gill, Ray & Buchanan, 1992).

2.3. Electrical measurements

Electrical measurements were taken between the 9th and 13th ribs of the LD muscle, at hourly intervals up to 8 h postmortem and again at 1, 2, 7 and 14 days, following excision of the muscle. Electrical measurements were taken by inserting electrodes into the muscle, perpendicular to the fibres and perpendicular to the long axis of the muscle without contact with fat. The depth of insertion of the probes was standardised using a depth gauge. After approximately 3 s, the measurement was recorded in the internal memory of the probe.

2.3.1. Electrical impedance

Electrical impedance (Py) was measured over a wide frequency range using the Meatcheck 160 (Sigma Electronic GmbH Erfurt, 2, Hauer Strabe 27, Haus 6, D-99091, Erfurt, Germany). The probes were inserted 6 cm into the LD muscle, with a 1.5 cm distance between the tips of the probes.

2.3.2. Electrical conductivity

Electrical conductivity (EC) was measured at a frequency of 1 kHz using a pork quality meter (PQM) (Intek GmbH, Industriestrabe 9, D-86551 Aichach, Germany). The electrical conductivity instrument consisted of two electrodes, 1 cm apart, which were inserted a distance of 4.5 cm into LD muscle.

2.4. Warner–Bratzler shear force

Steaks (2.5 cm thick) frozen at either 2, 7 and 14 days of ageing (frozen <8 wk), were thawed and tempered for approximately 18 h at 4°C. Cooking was performed by immersion within a plastic bag in a 72°C water bath (Grant, model Y38) to an internal temperature of 70°C. The internal temperature of each steak was monitored by use of a temperature probe (Hanna, model HI9041) placed in the geometric centre of each steak. Cores ($n=7$) of 1.25 cm in diameter were removed from each sample parallel to the muscle fibre direction with a hand coring device. Shear force measurements were made using a Warner Bratzler-shear device with a vee-shaped blade, attached to an Instron Universal Testing machine (Model 4464) (Shackelford et al., 1991).

2.5. Sensory analysis

Steaks were removed from frozen storage and allowed to thaw. They were then removed from vacuum packages and grilled to an internal temperature of 70°C according to the American Meat Science Association Research Guidelines for Cookery, Sensory Evaluation and Instrumental Tenderness Measurements of Fresh Meats (AMSA, 1995). The internal temperature of each steak was monitored by use of a temperature probe (Hanna, model HI9041) placed in the geometric centre of each steak. Sensory attributes were evaluated on samples served immediately after cooking. Panelists were asked to evaluate the steaks for tenderness, juiciness, flavour, texture and overall acceptability using a hedonic scale ranging from 1 to 8 for tenderness and juiciness and from 1 to 6 for the other quality attributes. The panel consisted of eight in-house trained assessors. Training was carried out over a 2–3 week period. Objectives of training were to familiarise each individual with test procedures, to improve their ability to recognise and identify sensory attributes and to improve their sensitivity and memory, permitting precise and consistent sensory judgements.

3. Results and discussion

3.1. Changes in pH during rigor development

Muscle pH is lowered during postmortem storage of muscle as a result of accumulation of lactic acid during glycolysis (Honikel, 1992). Fig. 1 represents the average pH fall for the 47 animals used in this study, which declined from an average value of 6.56 at 2 h postmortem to 5.48 at 24 h postmortem. No animal treatments were employed and no DFD (dark, firm and dry) carcasses were identified in this study. In general, the rate of pH fall was similar for all animals with the exception of 2 fast glycolysing muscles which reached their ultimate pH values (5.4 and 5.5) by 6 h postmortem. Ultimate pH values were found to be normal with low variation existing between animals.

3.2. Changes in temperature during rigor development

Processing conditions have a marked influence on tenderness, in particular, the temperature of meat conditioning. Fast chilling of carcasses, for instance, may induce a rapid temperature decline in superficial muscles, leading to cold shortening and resultant toughening. (Geesink, Koolmees, van Laack & Smulders, 1995) Variation in the rate of temperature fall between animals was minimised as much as possible by ambient temperature control. Fig. 2 shows the mean temperature profile of the muscles monitored in this study. According to Lee (1986) and May et al. (1992) muscle temperature is an important factor in the development of meat tenderness during ageing. A high muscle temperature postmortem accelerates the rate of pH decline in muscle (Busch, Parrish & Goll, (1967), presumably because such conditions permit enzymatic activity to continue (Buts, Claeys & Demeyer, 1987).

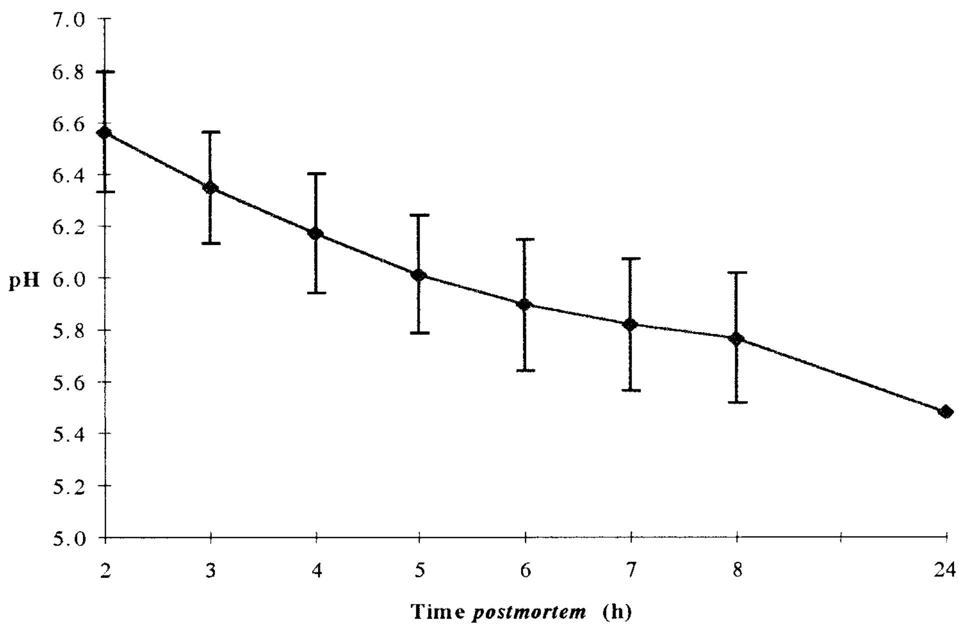

Fig. 1. Mean postmortem pH decline [± standard deviation (I)] of bovine *M. longissimus dorsi* during the first 24 h postmortem ($n = 47$).

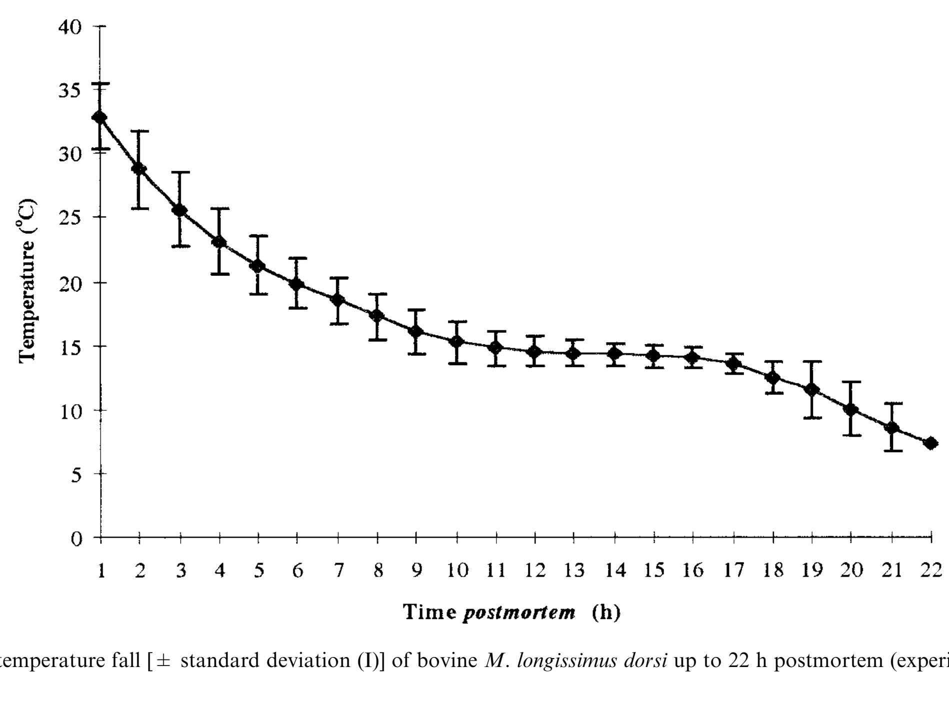

Fig. 2. Mean temperature fall [± standard deviation (I)] of bovine *M. longissimus dorsi* up to 22 h postmortem (experiment 1, $n = 19$).

3.3. Postmortem changes in electrical properties

3.3.1. Electrical impedance (Py)

The dimensionless Py value scale goes from 0 (aqueous medium) to 100 (intact medium). Py values increased slightly between 1 and 2 h, a finding also reported by Pliquett, Pliquett, Schoberlein and Freywald (1995) who suggested that this may be due to the swelling of cells. This causes an increase in impedance due to decreased extra-cellular volume, i.e. less ion-containing extra-cellular fluid is available to facilitate the flow of electric current. Py values did not change significantly up to 8 h postmortem after which time a significant decrease ($p < 0.001$) was noted at each measurement time from an average value of 73.6 at 8 h postmortem to 4.8 at 14 days postmortem (Fig. 3). Large variations in Py values were observed at 1 day (6–77) and 2 days (5–58) postmortem. It is worth noting however, that two fast glycolysing muscles were observed in this experiment and these also showed fast changes in electrical impedance (Table 1), reaching Py values of 6 and 12 at 1 day postmortem while the control sample had a Py value of 68 at this time. The increase in volume of extra-cellular fluid postmortem, caused by leaky membrane structures and decreased water holding capacity, is probably responsible for this marked decrease in electrical impedance. Although there appears to be a high range of electrical properties in this experiment, removal of these two samples would lower the range of Py values dramatically (40 – 77 and 20–68 for 1 and 2 days, respectively) which indicates an uneven distribution within the data set.

3.3.2. Electrical conductivity (EC)

EC is a means of testing the intact cell membranes within a muscle tissue (Honikel, 1993). A completely intact muscle tissue will have a low EC value which rises with an increase of fluids within the muscle. EC values increased significantly ($p < 0.001$) with ageing at each measurement time from 8 h to 14 days postmortem, from an average of 2 mS/cm at 8 h postmortem to 14.3 mS/cm at 14 days postmortem (Fig. 4). However, as for

Table 1
Changes in electrical impedance (Py), electrical conductivity (EC) and pH values of two fast glycolysing (FG) muscles identified in this experiment relative to a control or intermediate glycolysing muscle

	Py							
	7 h	8 h	1 day	2 days	7 days	14 days		
Control	71	72	68	42	15	5		
FG1	62	53	6	5	3	3		
FG2	69	51	12	10	4	3		
	EC							
	7 h	8 h	1 day	2 days	7 days	14 days		
Control	3.4	2.4	2.3	5.4	8.6	14.6		
FG1	2.8	3.9	13.7	13.5	15.9	17.1		
FG2	3.0	2.8	5.8	7.1	13.4	15.1		
	pH							
	2 h	3 h	4 h	5 h	6 h	7 h	8 h	1 day
Control	6.40	6.32	5.86	5.80	5.56	5.42	5.50	5.50
FG1	6.26	6.14	5.90	5.63	5.40	5.44	5.41	5.44
FG2	6.19	5.91	5.80	5.65	5.50	5.44	5.49	5.49

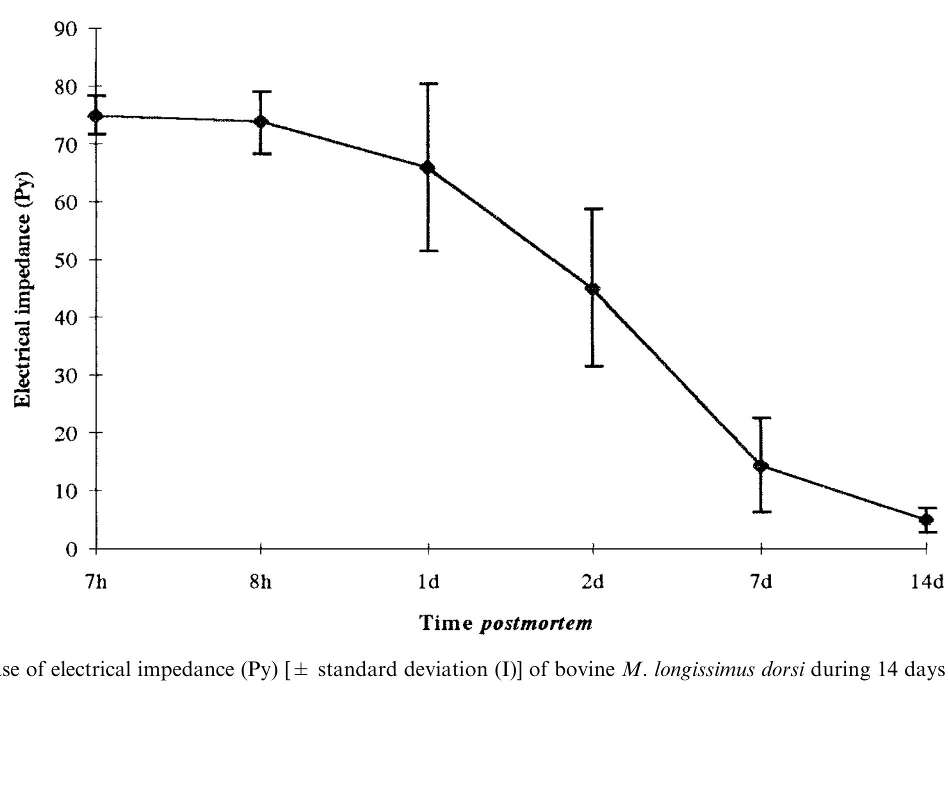

Fig. 3. Decrease of electrical impedance (Py) [± standard deviation (I)] of bovine *M. longissimus dorsi* during 14 days ageing ($n = 47$).

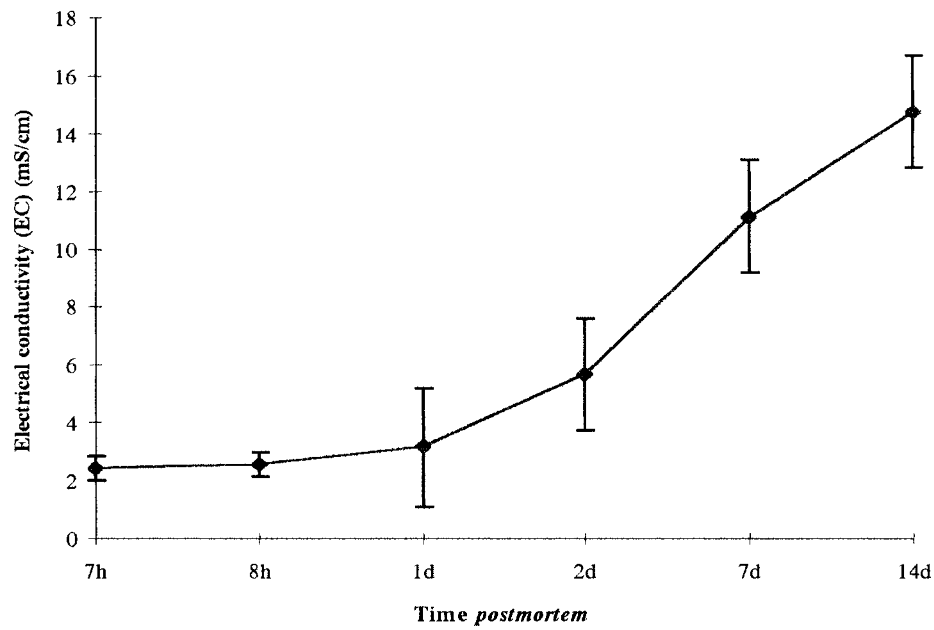

Fig. 4. Increase of electrical conductivity (mS/cm) [± standard deviation (I)] of bovine *M. longissimus dorsi* during 14 days ageing ($n=47$).

Py, EC values showed no change during the first 8 h after slaughter. Fast glycolysing muscles showed a faster increase in conductivity (Table 1). As explained above, enhanced conductivity with time postmortem is probably a result of increased of extra-cellular volume, caused by leaky membrane structures and decreased water holding capacity of the myofilaments. A wide range of EC values was observed at 1 (1.3–13.7 mS/cm), 2 (2.3–13.5 mS/cm), 7 (6.1–15.9 mS/cm) and 14 days (6.0–17.4 mS/cm) postmortem. However, as for Py at 1 and 2 days postmortem, an uneven distribution over the range of values was noted with very few samples having high EC values (> 9 mS/cm) at these times.

3.4. Relationship between pH and electrical properties of muscle

As early as 1936, it was proven by Callow that electrical impedance was related to pH. This relationship was exploited to make impedance the first method used for the on-line evaluation of meat quality, with many advantages over early pH meters (Swatland, 1995), and was used to supplement pH measurements, to demonstrate that DFD was caused by transport and fighting prior to slaughter (Bendall & Swatland, 1988). The electrical properties of meat are related to pH in some way but probably only via a mutual or shared relationship with ATP (Swatland, 1995). Most of the previously published work on the electrical properties of muscle tissue has concentrated on the detection of PSE (pale, soft and exudative) and DFD (dark, firm and dry) meat. Several workers have suggested that electrical conductivity is of value in identifying PSE (Garrido, Pedauye, Banon, Lopez & Laencina, 1995; Oliver, Gispert, Tibau & Diestre, 1991; Reichert 1996; Warriss, Brown & Adams 1991 but not DFD carcasses (MacDougall & Jones, 1980; Warriss et al., 1991). It has been suggested that electrical conductivity measurements were better at detecting PSE than the traditional pH muscle measurements (Garrido et al., 1995; Oliver et al., 1991). However, predictions may be unreliable soon after slaughter (Fortin & Raymond, 1988; Warriss et al., 1991).

Two fast glycolysing muscles which were identified in this experiment, also exhibited rapid changes in passive electrical properties which indicates the existence of some relationship between electrical properties and the rate of glycolysis (Table 1). Simple correlation coefficients were calculated to determine the statistical relationship between electrical measurements and pH values. The correlation coefficient (r) is a mathematical expression of how variations in one measured factor appear to be associated with variations in another. The closer this value is to -1 or $+1$, the closer is the association between the two factors (Szewczyk, 1968).

Py values taken between 7 h and 7 days postmortem were significantly correlated with pH measurements, taken between 2 h and 8 h inclusively (Table 2). The most highly significant correlations ($r=0.45$–0.62, $p<0.01$–0.001) were found with 2 days electrical measurements. pH measurements taken at 2, 5 and 7 h showed the most significant correlations ($p<0.001$) (Table 2). In agreement with Callow's earlier work, this study demonstrates a relationship between electrical impedance and pH. However, 14 day Py values were not significantly correlated with pH values ($r=0.14$–0.24, $p>0.05$). Honikel (1995) demonstrated strong correlation coefficients between pH at 45 min and Py at 45 min ($r=0.64$–0.68) and 3 h ($r=0.65$) in pork and concluded that impedance is a more reliable method than conductivity in determining PSE muscle.

In this study, EC values were also significantly correlated with pH at various times postmortem (Table 3), although correlations were lower in some cases than those obtained for impedance. The highest correlation with pH was with EC_{7h} values, with coefficients in the range 0.47–0.59 ($p<0.01$). pH_{24h} was not significantly correlated with EC values ($r=-0.012$–0.250, $p>0.05$). Warriss et al. (1991) also carried out an experiment to relate conductivity measurements to pH and reported that conductivity measurements made at 45 min and 20 h postmortem were moderately correlated ($r=0.54$–0.62) with initial pH (pH_{45}).

A number of other experiments have also demonstrated a relationship between conductivity and pH values 40–50 min postmortem. The correlation coefficients were $r=-0.51$ (Schmitten, Schepers, Jungst, Reul & Festerling, 1984), $r=-0.67$ (Sack, Branscheid, Oster & Fewson, 1987) and $r=-0.58$ (Sack & Branscheid, 1990). However, Jaud et al. (1992) found large variations in the EC_{45} values for muscles in the same pH range. Also Feldhusen et al. (1987) suggested that changes in EC occur at a very different rate from pH, especially when glycolysis has been very rapid. This may explain why conductivity (Jaud, Weisse, Gehen & Fisher, 1992) and capacitance (Fortin & Raymond, 1988; Warriss et al., 1991) measurements may be unreliable soon after slaughter, for the prediction of PSE characteristics in pork. More recent work has provided similar information on the delayed pattern of change of EC as compared with the pH drop postmortem (Eggert, Mohr & Kalm, 1990; Sack & Branscheid, 1990; Sack et al., 1987). These workers also describe closer relationships between EC_{24} and pH. Warriss et al. reported that EC_{45} and EC_{20h} measurements were moderately correlated ($r=0.54$–0.62) with initial pH (pH_{45}). All of the work described above was carried out on porcine muscle.

Correlation coefficients (Tables 2 and 3) between electrical measurements and pH and the very rapid changes in electrical properties of the 2 fast glycolysing muscles in this study suggests that some kind of relationship exists. Had a higher number of fast glycolysing and perhaps some slower glycolysing muscles been identified in this study, higher relationships may have been found.

3.5. *Changes in meat quality attributes and their relationship to muscle electrical properties*

3.5.1. *Sensory analysis*

Both tenderness and texture improved significantly ($p<0.001$) during the ageing period in this study with highest scores reported for 14 days samples (Table 4). These sensory attributes were also found to be intercorrelated at 2 ($r=0.69$, $p<0.001$), 7 ($r=0.69$, $p<0.001$) and 14 days postmortem ($r=0.59$, $p<0.001$). Overall acceptability also increased significantly ($p<0.001$) during ageing which is probably related to the increase in tenderness and texture, since consumer acceptance is largely based on these sensory attributes. Also, overall acceptability was found to be significantly correlated with tenderness ($r=0.87$, 0.65, 0.54, $p<0.01$–0.001) and texture ($r=0.76$, 0.75, 0.80, $p<0.001$) at 2, 7, and 14 days postmortem, respectively. Flavour, a major consideration for consumer acceptance of meat, is known to improve with ageing (Wang, Maga & Bechtel, 1996). A small but significant ($p<0.001$) increase in flavour was detected during postmortem storage of meat in this study (Table 4). According to Shahidi (1994), flavour is an important sensory aspect of the overall acceptability of meat. Therefore, like tenderness and texture, this improvement in flavour is likely to have had an influence on overall acceptability scores, although this attribute was not found to be as highly related to overall acceptability at 2 ($r=0.32$, $p<0.05$), 7 ($r=0.14$, $p>0.05$) and 14 days ($r=0.59$, $p<0.01$) as were tenderness and texture scores. No change ($p>0.05$) in sensory juiciness was noted over the ageing period and this attribute was not correlated with overall acceptability at any of the measurement times.

According to Warriss et al. (1991), the electrical characteristics of muscle change with time postmortem and may be used to predict meat quality. Pliquett et

Table 2
Simple correlation coefficients obtained between electrical impedance, measured between 7 h and 14 days postmortem and pH at 2, 5 and 7 h postmortem[a]

	Electrical impedance					
	7 h	8 h	1 day	2 days	7 days	14 days
pH_{2h}	0.41 **	0.50 **	0.43 **	0.62 ***	0.41 **	NS
pH_{5h}	0.52 **	0.54 **	0.54 **	0.60 ***	0.37 *	NS
pH_{7h}	0.54 **	0.51 **	0.52 **	0.60 ***	0.43 **	NS

[a] Significance level: ***$p<0.001$, **$p<0.01$, *$p<0.05$, NS = not significant.

Table 3
Simple correlation coefficients obtained between electrical conductivity, measured between 7 h and 14 d postmortem and pH at 2, 5 and 7 h postmortem[a]

	Electrical conductivity					
	7 h	8 h	1 day	2 days	7 days	14 days
pH_2	−0.48 **	−0.41 **	−0.37 *	−0.53 **	−0.30 *	NS
pH_5	−0.58 **	−0.53 **	−0.47 **	−0.49 **	NS	NS
pH_7	−0.57 **	−0.45 **	−0.41 **	−0.45 **	NS	NS

[a] Significance level: ***$p<0.001$, **$p<0.01$, *$p<0.05$, NS = not significant.

Table 4
Summary sensory scores for tenderness, texture, overall acceptability, juiciness and flavour of bovine *M. longissimus dorsi* ($n=47$) at 2, 7 and 14 days postmortem

Sensory attribute	Mean[e]	Range	Standard deviation
Tenderness[a]			
2 days	4.4a	2.1–6.4	0.9
7 days	5.4b	3.9–6.8	0.7
14 days	6.0c	4.5–7.4	0.6
Texture[b]			
2 days	3.4a	1.9–4.6	0.7
7 days	3.7b	2.5–4.6	0.4
14 days	4.0c	3.1–4.6	0.3
Overall acceptability[c]			
2 days	3.2a	1.8–4.3	0.6
7 days	3.9b	2.8–4.6	0.4
14 days	4.1c	3.3–4.9	0.4
Juiciness[d]			
2 days	5.2a	3.3–6.6	0.8
7 days	5.2a	3.6–6.8	0.8
14 days	5.1a	3.4–6.6	0.8
Flavour[c]			
2 days	3.7a	3.1–4.3	0.3
7 days	4.1b	3.4–5.0	0.4
14 days	4.0b	3.4–4.6	0.3

[a] 1 = Extremely tough, 8 = extremely tender.
[b] 1 = Very poor, 6 = extremely good.
[c] 1 = Not acceptable, 6 = extremely acceptable.
[d] 1 = Extremely dry, 8 = extremely juicy.
[e] Means for each sensory attribute with different letters are significantly different ($p<0.001$).

Table 5
Correlation coefficients obtained between 2 day juiciness scores and selected electrical impedance (Py) and conductivity (EC) measurements of bovine *M. longissimus dorsi* stored at 4°C up to 14 days postmortem[a]

	Py_{8h}	Py_{1d}	Py_{7d}	EC_{8h}	EC_{1d}	EC_{7d}
Juiciness (2 days)	0.33 *	0.33 *	0.46**	NS	NS	−0.43**

[a] Significance level: ** $p<0.01$, * $p<0.05$, NS = not significant.

al. (1990), stated that passive electrical parameters are suitable for characterising quality in terms of drip loss, colour brightness, and the degree of ageing of meat. A few low but significant correlations were found between sensory attributes and electrical properties measured at specific times postmortem. Juiciness at 2 days postmortem exhibited the highest number of correlations with electrical measurements and was found to be more significantly related to impedance (Py) than conductivity (EC) (Table 5). Only one other significant correlation was found between juiciness and EC, that of juiciness at 2 days with EC_{7d} ($r=-0.43$, $p<0.01$). A few other weak correlations ($r=-0.33$, -0.36, -0.33, $p<0.05$) were found between Py_{14d} and texture (2 days), overall acceptability (2 days) and tenderness (7 days), respectively. However, this late postmortem measurement (i.e. Py_{14d}) would be of little use in meat quality prediction. No correlations were found to exist between 14 days sensory data and electrical properties with the exception of juiciness and flavour which were weakly correlated with EC_{2d} ($r=-0.30$, $p<0.05$) and EC_{8h} ($r=-0.38$, $p<0.05$), respectively. Fourteen day sensory data is of particular interest since it is more representative of ultimate meat quality than earlier sensory evaluations. Fig. 5 illustrates the non-significant relationship found between Py_{2d} and sensory tenderness at 2 ($r=-0.13$, $p>0.05$) and 14 days postmortem ($r=-0.04$, $p>0.05$). No previous literature was cited which related sensory attributes of meat with electrical measurements.

Correlations with earlier electrical measurements were not significant. Late postmortem measurements (i.e. 7 and 14 days) are of little value to the meat processor as 'predictors' of meat quality. However, if they are found to have a strong relationship with meat quality, they may have a use in aged meat quality evaluation/confirmation. As mentioned earlier, 14 days sensory attributes are more representative of ultimate meat quality. However, in this experiment, 14 days sensory attributes did not correlate significantly with any of the electrical measurements taken at specific times postmortem. These results demonstrate that these measurements would be of little value as predictors of beef meat quality.

3.6. Warner–Bratzler shear force (WBSF)

Mean WBSF values decreased significantly ($p<0.001$) over the ageing period from 7.21 kg at 2 days postmortem, to 5.08 kg at 7 days postmortem, to 3.8 kg at 14 days postmortem (Table 6), indicating a significant improvement in tenderness. WBSF also correlated with sensory tenderness scores at 2 ($r=-0.63$, $p<0.001$), 7 ($r=-0.66$, $p<0.001$) and 14 days postmortem ($r=-0.53$, $p<0.01$). Shear force values were also significantly correlated with texture and overall acceptability at 2 and 7 days postmortem ($r=-0.41$ to -0.63, respectively, $p<0.01$–0.001).

Few significant correlations existed between shear force and electrical measurements. Two day shear force values were only weakly correlated with Py_{7d} ($r=0.37$, $p<0.05$) and Py_{14d} ($r=0.33$, $p<0.05$) postmortem, and 7 days WBSF values correlated weakly with Py_{14d} ($r=0.33$, $p<0.05$). Shear force values were not found to correlate with any other Py value or with any of the electrical conductivity values. A scatterplot of EC_{2d} versus WBSF at 7 and 14 days postmortem is a clear indication of the lack of relationship between electrical conductivity and shear force values (Fig. 6). Correlation coefficients were calculated to be −0.18 and −0.04, respectively, ($p>0.05$). Again, these results demonstrate

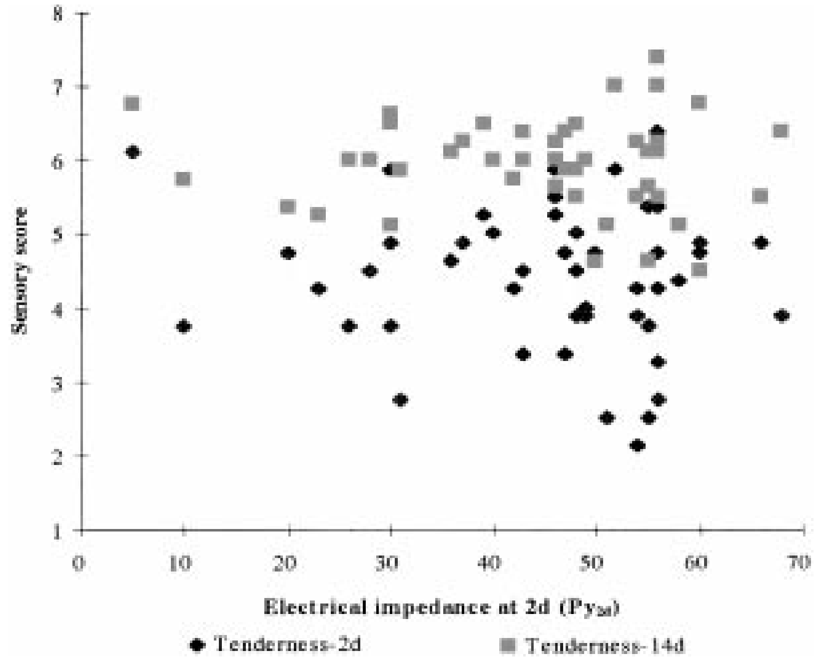

Fig. 5. Scatterplot showing the relationship between electrical impedance data at 2 days (Py_{2d}) and sensory tenderness scores at 2 days ($r=0.13$, $p>0.05$) and 14 days ($r=-0.04$, $p>0.05$) postmortem ($n=47$).

Table 6
Mean, range of values and standard deviations for Warner–Bratzler shear force (WBSF) values (kg per 1.25 cm core) at 2, 7, and 14 days postmortem of M. *longissimus dorsi* stored at 4°C

WBSF	Mean[a]	Range	Standard deviation
2 days	7.21a	3.89–14.65	2.02
7 days	5.08b	2.56–10.22	1.35
14 days	3.80c	2.36–6.16	0.84

[a] Means with different letters are significantly different ($p<0.001$).

that electrical measurements are not capable of predicting meat quality.

3.7. Water holding capacity

Drip loss and cook loss data are shown in Table 7. Drip loss was weakly correlated with EC and Py measurements: EC_{2d} ($r=0.36$, $p<0.05$), EC_{7d} ($r=0.33$, $p<0.05$), Py_{2d} ($r=-0.45$, $p<0.01$) and Py_{7d} ($r=-0.48$, $p<0.01$). No significant correlations were found with cook loss with the exception of cook loss at 7 days which was significantly correlated with EC_{14d} ($r=-0.40$, $p<0.01$), Py_{7d} ($r=0.44$, $p<0.01$) and Py_{14d} ($r=0.46$, $p<0.01$).

Previous work carried out on pork muscle using a different conductivity measurement instrument (LF 191) than the one used in this study, indicates no uniform relationship between electrical conductivity at 45 min and percentage drip loss (Jaud et al., 1992). Work using another instrument (Tecpro pork quality meter) at 45 and 20 h postmortem showed correlation coefficients of 0.34 and 0.47, respectively, with drip loss. Greshake, Schmitten and Schepers (1988), cited in Jaud et al. (1992), calculated a correlation of 0.73 between EC_{1d} and drip loss of porcine muscle. The feasibility of using electrical measurements as a parameter when judging meat quality attributes, including drip and cook loss, is based on the fact that, as a result of various degrees of damage to the membrane during postmortem glycolysis at high temperatures in the musculature, the exchange of ion-containing, intra-cellular fluid and thus the electrical properties of the system are altered.

3.8. Colour

The appearance of meat, in particular its colour, is the main factor affecting acceptability at retail (Moore 1990; Romans & Norton, 1989). The colour of the muscle surface is determined mainly by both the amount and the redox state of myoglobin (Fox, 1987). Impact and penetration of oxygen at the muscle surface cause rapid oxygenation of the purplish-red myoglobin to bright red oxymyoglobin and slow auto oxidation to brown metmyoglobin (Feldhusen, Warnatz, Erdmann & Weizel, 1995). Hunter Lab colour parameters changed significantly ($p<0.001$) during the storage period. Hunter 'a' value increased from 11.1 at 2 days postmortem to 15.6 at 14 days postmortem indicating an increase in redness due to an increase in oxymyoglobin concentration in the muscle surface. Some HunterLab colour values correlated weakly with electrical measurements (Table 8) but correlations are too low to be of any practical use.

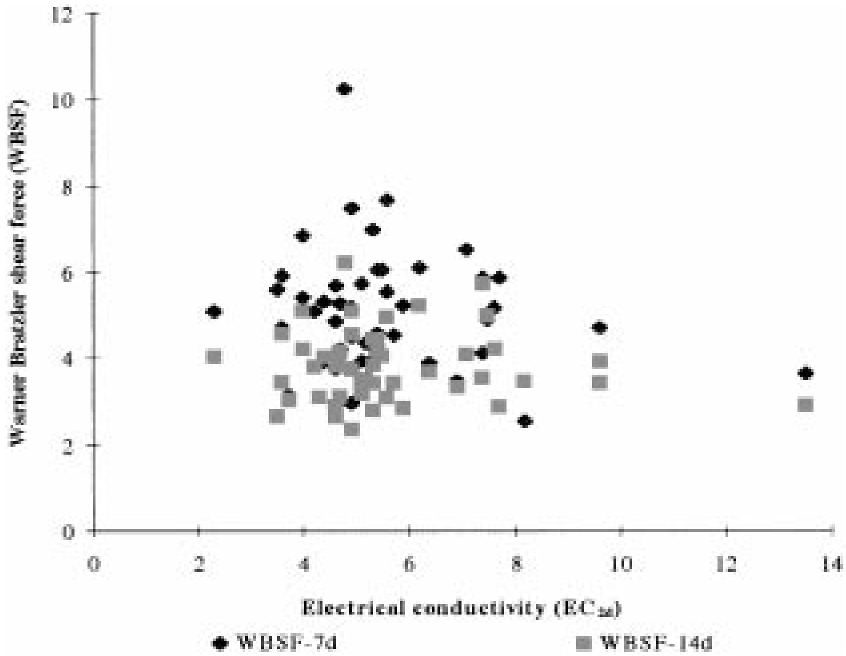

Fig. 6. Scatterplot showing the relationship between electrical conductivity at 2 days postmortem (EC_{2d}) and Warner–Bratzler shear force (WBSF) values at 7 days ($r = -0.182$, $p > 0.05$) and 14 days ($r = -0.04$, $p > 0.05$) postmortem ($n = 47$).

Table 7
Mean, range of values and deviations for drip loss and cook loss values (%) of bovine M. *longissimus dorsi* ($n = 47$) stored at 4°C up to 14 days *postmortem*

Quality attribute	Mean[a]	Range	Standard deviation
Drip loss			
2 days	1.88	0.14–3.89	0.98
Cook loss			
2 days	28.55a	15.40–34.54	3.94
7 days	29.34a	18.07–37.26	4.03
14 days	30.41a	24.7–36.97	2.80

[a] Means with the same letters are not significantly different ($p < 0.05$).

Table 8
Simple correlation coefficients obtained between electrical measurements and Hunter Lab colour parameters ($n = 47$)[a]

Hunter colour parameter	Py_{8h}[c]	Py_{1d}	EC_{8h}[b]	EC_{1d}
Hunter L *values*				
7 days	−0.31 *	NS	NS	NS
14 days	NS	−0.34*	NS	NS
Hunter a *value*				
7 days	NS	0.37 *	−0.31 *	−0.32 *
14 days	NS	NS	NS	NS
Hunter b *value*				
b_7	0.35 *	0.48 **	−0.32 *	−0.39 *
b_{14}	0.33*	0.38*	NS	−0.32*

[a] Significance level: **$p < 0.01$, *$p < 0.05$, NS = not significant.
[b] EC = electrical conductivity.
[c] Py = electrical impedance.

3.9. Relationship between electrical properties and meat quality attributes measured over the ageing period

The previous work has dealt exclusively with the relationship between electrical measurements and meat quality attributes at specific times postmortem. Poor relationships were thought to be due to a restricted range in meat quality. Further calculations have been carried out to determine the relationship between electrical characteristics measured over the ageing period, at 2, 7 and 14 days and meat quality attributes evaluated at the same times, since this would undoubtedly incorporate a wider range in quality (Table 9).

Electrical measurements were moderate to highly correlated with WBSF, sensory tenderness and overall acceptability (Table 9) with electrical impedance showing the highest correlation coefficients ($r = 0.68$, -0.60 and -0.58, $p < 0.001$) with these three attributes respectively. Hunter '*a*' and '*b*' colour parameters were also moderate to highly correlated with Py ($r = -0.66$, -0.57, $p < 0.001$) and EC ($r = 0.65$, 0.56, $p < 0.001$), respectively. Improved correlation coefficients here, as opposed to those calculated for specific time points, is probably solely due to the wider range in meat quality attributes achieved by including meat quality data from all time points. Hunter '*L*' value, juiciness, cook loss

Table 9
Simple correlation coefficients obtained between electrical properties and selected meat quality attributes of bovine *M. longissimus dorsi* evaluated over the same ageing period (2, 7 and 14 days postmortem)

	Py[a]	EC[a]
Warner–Bratzler shear force	0.68***	−0.65***
Tenderness	−0.60***	0.56***
Juiciness	NS	NS
Flavour	−0.36***	0.31***
Texture	−0.35***	0.36***
Overall acceptability	−0.58***	0.55***

[a] Significance level: ***$p<0.001$, **$p<0.01$, *$p<0.05$, NS = not significant.

and sarcomere length, measured over the ageing period were not significantly correlated with either electrical measurement. While these results do not demonstrate an ability of these measurements to predict meat quality, these results show that electrical measurements taken over the ageing period can determine the extent of ageing of muscle and give an indication of the meat quality in terms of WBSF and sensory tenderness and overall acceptability.

4. Conclusions

During the development of rigor, complex electrical changes occur. Significant correlations were obtained between the rate of pH fall and conductivity and impedance measurements. It is clear from this study that electrical properties are related in some way to the rate of postmortem glycolysis with fast and slow glycolysing muscles clearly demonstrating the fastest and slowest rates of change in electrical properties, respectively. Results of this study demonstrate that early postmortem electrical measurements are not suitable for the prediction of beef meat quality. Further work examining early electrical measurements of pork or lamb may prove more promising since postmortem biochemical changes occur at a much faster rate in these compared with beef. Electrical measurements taken over the ageing period (at 2, 7 and 14 days) were moderate to highly correlated to meat quality attributes measured over the same time period. In particular, WBSF, sensory tenderness and overall acceptability and Hunter '*a*' and '*b*' colour values were well correlated with electrical impedance and conductivity, respectively; demonstrating that electrical properties of muscle tissue can indicate the extent of muscle ageing and show great potential for use as indicators of meat quality. Therefore, these rapid physical measurements may be useful as meat quality indicators as they are also well suited for use on the slaughter line. Work is ongoing to examine the muscle fibre membrane integrity in relation to muscle electrical properties.

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