



THE EFFECTS OF BEEF CARCASSES HIGH VOLTAGE ELECTRICAL STIMULATION AND ROASTING METHODS ON TENDERNESS AND WATER RETENTION OF BEEF

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Received 22 September 2017; accepted 15 March 2018; available online 22 March 2018.

Key words: electrical stimulation, beef, roasting, tenderness, WHC, cooking loss.

Abstract

The aim of the study was to determine the effect of high voltage electrical stimulation (330 V, 17 Hz, 120 s) of beef half-carcass and heat treatment on tenderness and water holding capacity of meat. The experimental material was a *semimembranosus* muscle derived from Polish Holstein-Friesian heifers ($n=12$). In the experiment, a forced and natural air circulation ovens were used; the raw material was heated at 170°C to obtain a final temperature from 55 to 80°C inside the beef. Results showed that electrical stimulation improved tenderness of roasted beef, which was demonstrated in the decrease in the maximum shear force from 39% to 26%. The electrical stimulation had a negative effect on cooking losses during roasting and water content in the final product. It has also been shown that studied quality attributes of beef depends on the type of heat treatment. Beef prepared in forced air circulation oven, were characterized by lower water content and higher values of maximum shear and compression forces than those heated in natural air circulation oven.

Subscripts

ES – electrically stimulated sample,

C – control sample,

NC – heat treated in natural air circulation oven,

FC – heat treated in forced air circulation oven.

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Introduction

Electrical stimulation of carcasses of slaughter animals is one of the technological treatments that are aimed at improving the sensory attributes of meat, in particular tenderness (FERGUSON et al. 2000, HWANG et al. 2003, KIM et al. 2013). This method consists in carcass muscle tissue exposure to the impact of an electric current imitating nervous impulses, within the first hour after slaughter (RING, TAYLOR 1988, ROGOW, MOJSENKO 1981, ŻYWICA 1998). Endogenous biochemical and ultrastructural transformations induced by electrical stimulation effect a change in post-slaughter properties of the muscle tissue. This change is manifested by increased tenderness, elongated stability, as well as improved flavor, juiciness, and color of the tissue (DEVINE et al. 1999, GEESINK et al. 1994, PALEARI et al. 1991, RASHID et al. 1983).

The improvement of these traits of meat increases its eating and processing usability. For this reason, electrical stimulation is applied to process of beef and lamb meat (BOUTON et al. 1980, EIKELENBOOM et al. 1985, HWANG et al. 2003, JONES et al. 1991, TOOHEY et al. 2008), and also to improve quality attributes of meat from such animals as alpacas (SMITH et al. 2016), donkeys (POLIDORI et al. 2016), and goats (KADIM et al. 2014).

Based on long-standing investigations, the improvement of tenderness of electrically stimulated meat is believed to result from:

- activating the calpain enzymes, specifically μ -calpain, has been found to be responsible for the majority of postmortem proteolysis of muscle proteins associated with tenderness in the first 72 h postmortem (ANDERSON et al. 2012, FERGUSON et al. 2000, GEESINK et al. 1994, GEESINK et al. 2006, HUFF-LONERGAN et al. 2010),

- prevention of cold shortening through reducing the concentration of ATP and other high-energy phosphatides and through rapidly reduced pH owing to enhanced glycolysis (CHRYSTALL and DEVINE 1978, GARIEPY et al. 1995, HWANG et al. 2003, SOARES, AREAS 1995),

- physical damages inside the stimulated tissue (SORINMADE et al. 1982, ŻYWICA et al. 1998),

- increased activity of lysosomal enzymes, probably, the rapid decrease of pH accelerates the disruption of lysosomes, thereby causing release of proteases (cathepsin-C and β -glucuronidase) to the intra- and inter-cellular compartments at still high temperature (DUTSON, 1980, GEESINK et al. 1994, SOARES, AREAS 1995, SONAIYA et al. 1982),

- destabilization of collagen fibers (GEESINK et al. 1994, LESIÓW 1993).

Earlier studies demonstrated the highest rate of post-slaughter transformations of beef, accelerated by the electric current, to occur in the first 24 h post slaughter (GEESINK et al. 1994, POLIDORI et al. 1996, SOARES, AREAS 1995).

The non-stimulated beef needs to undergo the ageing process (lasting from 9 to 14 days) to develop all desirable sensory traits.

To get the full picture of the effect of electrical stimulation on the culinary quality of beef, a study was undertaken to analyze the dynamics of changes in the electrically stimulated muscle tissue after the first 48 h of carcass ageing under chill conditions in a meat processing plant. This objective was accomplished by determining the effect of high-voltage electrical stimulation of beef carcasses and the effect heat treatment under conditions of forced and natural air circulation on the tenderness and water holding capacity of roasted beef.

Materials and methods

The experimental material consisted on *semimembranosus* muscle from half-carcasses of heifers of Polish Holstein-Friesian breed of the Black-and-White variety ($n=12$) aged ca. 18 months and mean final body weight of 340 ± 22 kg. Animals were slaughtered according with the technology used in meat processing plants (ŻYWICA, BANACH 2014). Left half-carcasses, 40 min after slaughter, were subjected to electrical high voltage stimulation using a device of own construction applying 330 V AC, 17 Hz, for 120 s. Right half-carcasses were the controls. After ca. 48 h of storage in the cooling conditions ($\pm 4^\circ\text{C}$, 0.5 m s^{-1}), from the electrically stimulated (ES) and non-stimulated (C) half-carcasses *semimembranosus* muscles were cut, divided into a samples of ca. 300 g and dimensions $90\times 60\times 60$ mm ($n=72$). The samples were analysed without any further ageing. The pH of the samples was measured using a pH-meter type HI 8314 C equipped with a stiletto electrode FC 200. The samples were then heat-treated (temp. 170°C) in ovens: with natural (NC) and forced air convection (FC) to obtain in its geometrical center temperature: 55; 60; 65; 70; 75 and 80°C (monitored with thermocouples). Roasts were cooled to room temperature (22°C) for 60 min.

Texture of the analyzed material was evaluated with two types of tests performed using the INSTRON 45942 apparatus:

A. shear force test – a Warner-Bratzler single-knife system 2830-013 type. Ten cuboids with the cross-section area equal to 1 cm^2 were cut out (at 200 mm/min) from each sample perpendicular the muscle fibers. Peak or maximum shear force across the fibres was expressed in N.

B. compression test – a 2830-011 type piston, 30 mm in diameter and 10 mm in thickness. This test consisted in one-time compression of the samples to 50% of their initial height; with the direction of applied force being perpendicular to the direction of muscle fiber arrangement. Peak or maximum shear force across the fibres was expressed in N.

To determine water-holding capacity (WHC) of the samples, they were weighed before and after the compression test. Whatman No. 1 filter paper (Whatman

Laboratory Division, Maidstone, England) was placed under each sample, into which the drip caused by compression absorbed. The expressible water content was calculated from the formula:

$$\text{Expressible water content} = \frac{m_1 - m_2}{m_2} \cdot 100 [\%]$$

where:

m_1 – weight of meat sample [g],

m_2 – weight of filter paper without meat sample before pressing [g],

m_3 – weight of filter paper with meat juice after pressing [g].

The surface area of the trace of drip on the filter paper was measured using a computer system for image analysis with JAVA and MOCHA software (JANDEL SCIENTIFIC, SAN RAFAEL CA, USA).

Cooking losses were calculated as the percent in weight differences between the raw and roasted beef based on the raw weight. After thermal treatment, the samples were first left until reach the room temperature and then weighted. Water content in raw and roasted beef was determined using the oven drying method (drying at $103 \pm 2^\circ\text{C}$ to a constant weight, PN-ISO1442, 2000),

Data was first carefully examined to eliminate outliers. A general linear model (one-way ANOVA) was used to determine significant differences ($p < 0.05$) among samples with different temperatures and roasting conditions used in the experiments. Multiple comparisons were done by the Tukey's test. All statistical analyses were done using STATISTICA.10 software (StatSoft, Inc., Tulsa, OK, USA).

Results

The raw material collected for analyses was characterized by water content of 75%; no significant differences were demonstrated between the samples in this respect. Also, the samples did not differ in the pH value which reached 5.64 ± 0.05 (C) and 5.68 ± 0.07 (ES).

Effect of electrical stimulation and heating methods on cooking losses and water content in roasted beef

Regardless of raw material preparation method or type of the oven, the cooking losses and water content in the roasted beef depended on the final temperature inside the roast. Roasting temperature increase caused an increase in cooking losses and a decrease in water content in the products.

Table 1

Effects of electrical stimulation on cooking loss, water content and surface area of drip (mean values ± standard deviation) in roasted beef heated with natural air circulation

Final temperature [°C]	Cooking loss [%]			Water content [%]			Area of drip [cm ²]		
	C	ES	signifi-cance	C	ES	signifi-cance	C	ES	signifi-cance
55	14.95±0.38 ^A	18.40±0.47 ^A	**	71.11±0.21 ^E	70.76±0.24 ^E	NS	18.73±1.09 ^F	13.47±0.19 ^F	**
60	22.64±0.07 ^B	23.07±0.12 ^B	**	70.05±0.11 ^D	70.21±0.05 ^E	NS	13.22±0.01 ^E	12.00±0.10 ^E	**
65	24.04±0.44 ^C	29.87±0.47 ^C	**	68.95±0.01 ^C	67.40±0.05 ^D	**	10.94±0.45 ^D	7.79±0.52 ^D	**
70	30.80±0.05 ^D	31.77±0.02 ^D	**	67.64±0.05 ^B	67.28±0.12 ^D	NS	9.28±0.35 ^C	5.77±0.13 ^C	**
75	33.71±0.28 ^E	35.89±0.14 ^E	**	67.46±0.08 ^B	65.12±0.02 ^C	**	6.69±0.31 ^B	3.61±0.14 ^B	**
80	41.35±0.30 ^F	38.53±0.09 ^F	**	63.38±0.07 ^A	64.17±0.35 ^A	*	3.71±0.31 ^A	2.82±0.05 ^A	**

A-F – mean values in columns with different letters differ significantly at $P < 0.05$;
 ** – significance level $P < 0.01$; * – significance level $P < 0.05$; NS – non significant
 C – control sample
 ES – electrical stimulation sample

Table 2

Effects of electrical stimulation on cooking loss, water content and surface area of drip (mean values ± standard deviation) in roasted beef heated with forced air circulation

Final temperature [°C]	Cooking loss [%]			Water content [%]			Area of drip [cm ²]		
	C	ES	signifi-cance	C	ES	signifi-cance	C	ES	signifi-cance
55	25.71±0.39 ^A	26.50±0.47 ^A	NS	68.62±0.29 ^E	67.51±0.23 ^E	**	10.84±0.80 ^D	9.56±0.47 ^D	NS
60	32.28±0.58 ^B	33.72±0.21 ^B	*	68.58±0.38 ^E	65.96±0.02 ^D	**	9.30±0.63 ^D	8.57±0.24 ^D	NS
65	33.61±0.51 ^C	35.34±0.42 ^C	**	66.59±0.23 ^D	65.85±0.09 ^D	**	6.86±0.07 ^C	4.48±0.11 ^C	**
70	37.14±0.16 ^D	38.74±0.07 ^D	**	65.04±0.15 ^C	64.38±0.27 ^C	*	5.94±0.62 ^C	4.10±0.27 ^C	**
75	38.56±0.44 ^E	39.27±0.28 ^E	NS	64.10±0.09 ^B	63.51±0.12 ^B	**	3.79±0.09 ^B	3.15±0.13 ^B	**
80	39.12±0.23 ^E	39.95±0.43 ^E	NS	64.02±0.08 ^D	62.91±0.17 ^A	**	3.10±0.29 ^A	2.75±0.07 ^A	NS

A-E – mean values in columns with different letters differ significantly at $P < 0.05$;
 ** – significance level $P < 0.01$; * – significance level $P < 0.05$; NS – non significant
 C – control sample
 ES – electrical stimulation sample

Weight losses caused by NC treatment in the analyzed range of final temperatures were as follows: from 14.95% to 41.35% in the control samples, and from 18.40% to 38.53% in the stimulated samples (Tab. 1). The FC treatment caused higher than NC losses which ranged from 25.71% to 38.56% (C) and from 26,50% to 39,27% (ES) at temperatures between 55 °C and 75°C (Tab. 2). The samples heated to the internal temperature of 80°C were characterized by weight loss of 39% (C and ES). A similar value of weight loss (38.53%) was noted during the treatment of ES samples in the oven with natural air circulation. The electrical stimulation had a negative effect on weight losses during heat treatment. At each analyzed temperature, the NC treatment caused significantly higher weight losses in the ES samples ($p < 0.05$). Such a dependency was also noticed during FC treatment, but only at temperatures of 60°C, 65°C, and 70°C. The weight losses had a strong effect on water content of the samples. A higher water content was determined in the NC (71.11%–63.38%) than in the FC (68.62%–62.91%) roasted beef (Tab. 1, 2). The electrical stimulation had a negative effect on water content in the roasted beef; and this effect was particularly noticeable in FC roasted beef (Tab. 2). Regardless of the final temperature the samples were heated to, the content of water was significantly lower ($p < 0.05$) in the ES than in the C samples.

Effect of electrical stimulation and heating methods on tenderness and WHC of roasted beef

The value of the maximum shear force, used to evaluate meat tenderness, depended on the final temperature the meat was heated to and on the method of its preparation (C and ES). Regardless of the treatment method, the ES samples were characterized by a significantly lower ($p < 0.05$) value of the maximum shear force which was similar for both NC (27.9 N–49.7 N) and FC (27.3 N–54.2 N) samples – Figure 1.

The roasted beef made of non-stimulated meat, roasted in FC, was characterized by the maximum shear forces ranging from 49.6 N to 81.5 N, whereas shear force of the NC samples ranged from 31.6 N to 58.0 N (Fig. 1).

Results showed that ES improved meat tenderness, decreasing the maximum shear force from 39% (55–75°C FC) to 26% (70°C NC).

The force needed to induce 50% compression of the samples, as well as meat WHC, and drip area were influenced by both the final temperature of meat and the usage of electrical stimulation. Regardless of the heating method, the samples from the stimulated carcasses were characterized by a lower compression force compared to the control samples. The greatest impact of electrical stimulation on roasted beef compression force decrease was observed during

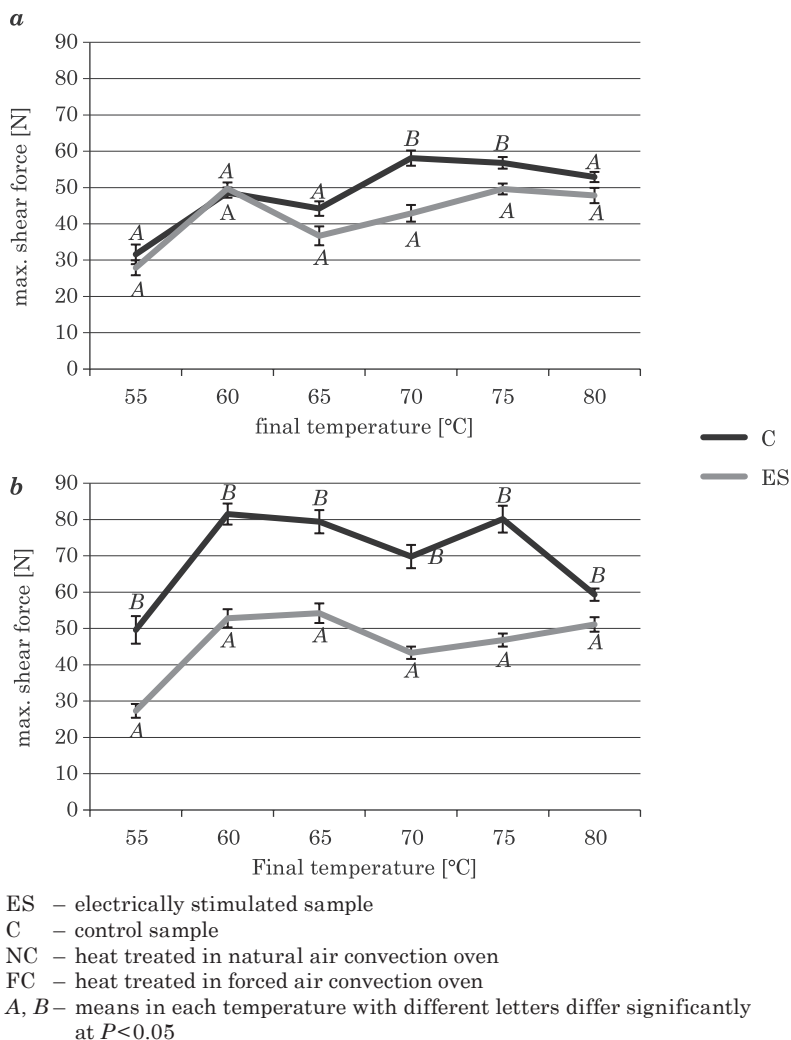
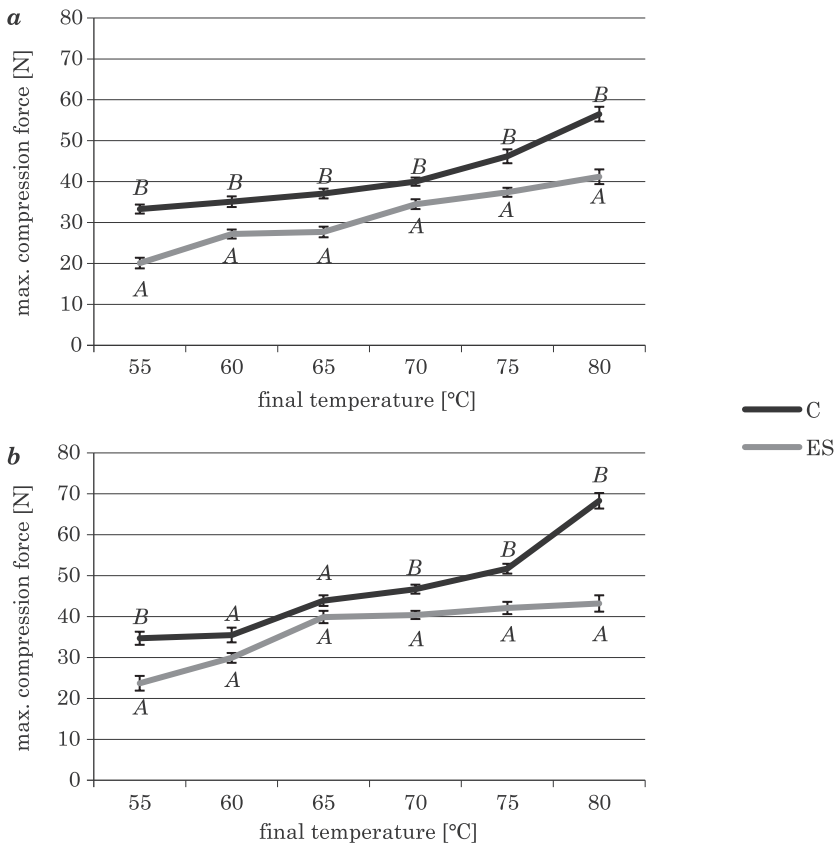


Fig. 1. Maximum shear force of the roasted beef depending on the final temperature: a – NC, b – FC

compression of the samples heated to 80°C. The maximum compression force of the ES roasted beef was lower by 27% (NC) and by 37% (FC) than that of the control samples (Fig. 2).

Higher values of the maximum compression force were determined in the FC (from 34.7 N to 68.3 N for C samples; from 23.7 N to 43.2 N for ES samples) than in the NC (from 33.3 N to 56.5 N for C samples; from 20.1 N to 41.2 N for ES samples) roasted beef (Fig. 2). An increase in the final temperature of samples caused a decrease in roasted beef WHC. The electrical stimulation diminished WHC of roasted beef in all analyzed variants.



ES – electrically stimulated sample

C – control sample

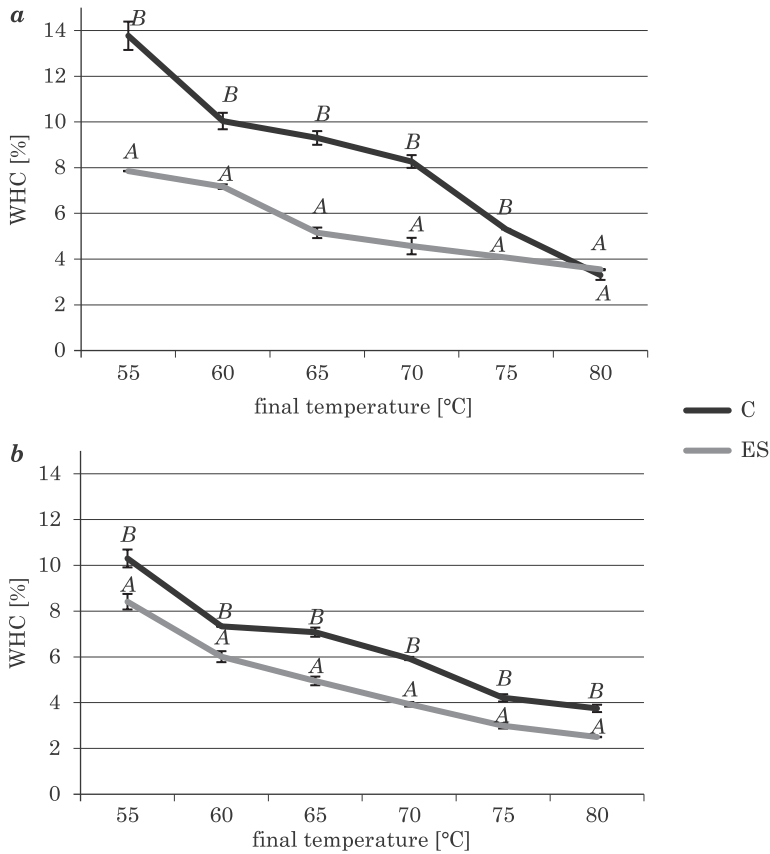
NC – heat treated in natural air convection oven

FC – heat treated in forced air convection oven

A, B – means in each temperature with different letters differ significantly at $P < 0.05$

Fig. 2. Maximum compression force of the roasted beef depending on the final temperature: a – NC, b – FC

Result showed that ES samples, both heated in NC and FC, were characterized by lower WHC compared to the control samples. For the NC-heated samples, the difference in WHC between the C and ES samples decreased along with an increase of the final temperature. This difference reached 5.52% in the roasted beef heated to 55°C, 4.15% in those heated to 65°C, 1.24% to 75°C, whereas no significant differences were noted in the roasted beef heated to 80°C (Fig. 3).



ES – electrically stimulated sample
 C – control sample
 NC – heat treated in natural air convection oven
 FC – heat treated in forced air convection oven
 A, B – means in each temperature with different letters differ significantly at $P < 0.05$

Fig. 3. Water-holding capacity (WHC) of the roasted beef depending on the final temperature: a – NC, b – FC

During FC heating, WHC of C samples was significantly higher ($p < 0.05$) than that of the ES samples in the whole range of the analyzed temperatures. This difference reached 1.89% in the samples heated to 55°C, 2.13% in those heated to 65°C, and 1.25% in the samples heated to 80°C (Fig. 3).

The one-way analysis of variance indicated a significant effect of both of factors: the final temperature and electrical stimulation on the studied quality attributes of the roasted beef.

Discussion

Effect of electrical stimulation and heating method on cooking losses, water content and WHC of roasted beef

Total cooking losses caused by the heat treatment depended primarily on the final temperature, rate of heating, and electrical stimulation treatment. Higher cooking losses in the FC samples may be attributed to the forced circulation of air which, apart from creating more favorable conditions for heat penetration, facilitates more intensive evaporation of water. In all samples, the increase of the losses was the fastest in a temperature range from 55°C to 70°C. This may be due to the fact that in this range of temperatures changes occur in two main structural proteins of meat: actomyosin complex and collagen. The extent of losses had a great effect upon WHC of the roasted beef. An increase in the final temperature inside the heated product was accompanied by a decrease in water content and WHC of the roasted beef, and in drip surface during compression.

Investigations addressing the effect of electrical stimulation on cooking losses indicate both a negative effect of this treatment on the analyzed trait (BOUTON et al. 1980, GEESINK et al. 1994), a lack of its effect on water holding capacity (BOWLES et al. 1983, POSPIECH et al. 1992, RASHID et al. 1983, SHIVAS et al. 1985) as well as its positive influence on the extent of losses (HOSTETLER et al. 1982, POWELL 1991, ROGOW, MOJSENKO 1981). HOSTETLER et al. (1982), who obtained a lesser by 6% drip during heating ES samples compared with C samples, pointed to the feasibility of increasing the number of water-binding sites in proteins as a result of structural changes induced by the flow of electric current. BOUTON et al. (1980), who compared C and ES samples (voltage from 45 V to 1,100 V), achieved higher scores for WHC in the case of the stimulated samples despite greater losses noted for these samples during heat treatment. On the other hand, SAVELL et al. (1981) demonstrated that WHC of the ES samples not to differ significantly from that of the C samples after 24 h of chill storage. But as the ripening time extended the difference between the C and ES samples was increasing, i.e. WHC of the ES samples decreased. In turn, POWELL (1991) and OLSSON et al. (1994) concluded that electrical stimulation contributes to a significant ($p < 0.05$) improvement of WHC, regardless of the age of animals and ripening duration. Some other authors indicate no effect of electrical stimulation on WHC of the products (BOWLES et al. 1983, SHIVAS et al. 1985).

A lower water content, WHC, and drip surface were demonstrated for the FC than for the NC heated samples. Alike results were published by other authors dealing with similar research issues who showed increased losses, decreased water content and WHC of roasted beef along with temperature increase (EIKELLENBOOM et al. 1998, NAEWBANIJ et al. 1983, PALKA et al. 1999).

Effect of electrical stimulation and heating method on tenderness of roasted beef

Results of the experiment allow concluding the electrical stimulation treatment improved tenderness of all samples and caused lesser differences between the maximum shear forces in the ES samples heated to temperatures from 55 to 80°C in both NC and FC. The FC-treated control samples were characterized by higher maximum shear forces than these heated in NC.

Changes in the maximum shear force are associated with transformations of proteins that are determined by temperature of the roasting process. The increase in the maximum shear forces at temperatures ranging between 55 and 60°C may be induced by denaturation of myofibrillar proteins of meat, myosin and α -actinin in particular, and by granulation of the epimysium. A decrease in the maximum shear force at 65°C, followed by its increase may be explained by the fact that at a temperature of ca. 65°C the denaturation process begins in muscle collagen, whereas changes observed at a temperature of ca. 70°C include fragmentation of myofibrils in the Z line coupled with denaturation of titins, and shrinkage of collagen fibers in the endomysium (FRITZ et al. 1992, MARTENS et al. 1982, PALKA, DAUN 1999). According to ZALEWSKI (1995), once the temperature of ca. 65°C is reached inside the muscle, there occurs a respective, small denaturation of muscle fiber proteins, which contributes to softness and WHC of a dish. PALKA and DAUN (1999) concluded that analyzed texture parameters, such as springiness, cohesiveness, chewiness, modulus of elasticity, initial stress, and hardness, changed during heating independently and their values increased along with temperature increase reaching their maxima in a temperature range from 70 to 100°C. EIKELENBOOM et al. (1998) also obtained the lowest value of the shear force for the samples heated at a temperature of 65°C. The course of values of the maximum compression force, presented by these author, is very similar to that shown in this paper.

Temperature increase during roasting caused an increase in the value of the maximum compression force in all analyzed samples. Results showed also the FC treatment to induce an increase in the maximum force during compression compared to the NC-heated samples. Presumably, this increase may be linked with structural changes of meat proteins and a lower water content in the FC-heated beef. This method of roasting makes meat more dry and more resistant during compression. It is generally accepted (PALKA, DAUN 1999) that heat-induced changes evoke a softening effect in the connective tissues and that denaturation of myofibrillar proteins causes the hardening effect. The culinary cut used in the study has very little collagen, hence the effect of hardening as a result of denaturation of myofibrillar proteins is especially tangible and is manifested by the increased maximum forces of shear and compression.

CONTRERAS-CASTILLO et al. (2016) found that the direct application of low-voltage electrical stimulation (104 V) on muscle did not significantly affect the rate of meat tenderisation or degradation of myofibrillar proteins in beef evaluated during post mortem ageing (up to 28 days pm).

The improvement of tenderness, presented in this paper, may be explained by the fact that electric current flow through a carcass causes physical damages inside the stimulated tissues, destabilization of collagen fibers, enhanced activity of lysosomal enzymes, as well as accelerated decrease in the activity of μ -calpains, and proteolysis of myofibrillar proteins (GEESINK et al. 1994, OSTOJA, KORZENIOWSKI 1992, SOARES, AREAS 1995, SONAIYA et al. 1982, ŻYWICA et al. 1998).

The positive effect of electrical stimulation on beef tenderness was also demonstrated by other authors who unanimously reported about its improvement as a result of this treatment (BOUTON et al. 1980, HOSTETTLER et al. 1982, PALEARI et al. 1991, POWELL 1991, SAVELL et al. 1981, RASHID et al. 1983, ROGOW, MOJSENKO 1981, SONAIYA et al. 1982).

Conclusions

Results of the study presented in this paper indicate a positive effect of electrical stimulation on tenderness of roasted beef. In most of the analyzed samples, regardless of the final temperature and heating method, lower shear and compression forces were achieved after the electrical stimulation.

It was shown also that investigated quality attributes of roasted beef depended on heating method. The beef obtained as a result of roasting in forced air circulation oven, were characterized by lower water content and higher shear and compression forces than those roasted in natural air circulation oven. Quality attributes varied depending on final temperature inside the beef cuts. The roasts prepared from electrical stimulation beef heated to 65 and 70°C in natural air circulation oven, had the best quality.

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