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2 The effect of the cooling rate of beef: the significance of pH at
3 7 °C in relation to tenderness

4

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9

10 **Abstract**

11

12 To study the effects of cooling regime on beef tenderness, seven commercial beef
13 slaughterhouses with different cooling regimes were selected to obtain different carcass
14 cooling rates. The pH values and temperatures of 8 *M. longissimus dorsi* (LD) and *M.*
15 *semimembranosus* (SM) muscles from each slaughterhouse were monitored for 30 h. The
16 muscles of the monitored carcasses were excised and vacuum packed for Allo-Kramer shear
17 force (SF) determinations. Samples were kept at 3-4 °C for 5 or 21 d.

18

19 The slaughterhouses were grouped by their average pH values of the muscles, prevailing at the
20 moment when the temperature of the muscles reached 7 °C. The pH groups for LD were (i)
21 low (5.52-5.63) (ii) medium (5.84-5.97) and (iii) high (6.16-6.17). The highest shear forces

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1 were in group (iii), being the toughest: 155 and 152 N/g, and the lowest in group (i) (the most
2 tender): 108 and 116 N/g, respectively. The regression equation for the shear force was $SF = -$
3 $295.4 + 73.0 * (\text{pH at } 7 \text{ } ^\circ\text{C})$; ($R^2 = 87\%$). There was no significant correlation between the
4 cooling rate and tenderness in SM, indicating that it is difficult to control the tenderness of all
5 the muscles by the same cooling regime. The ageing effect was more marked and the variation
6 in the shear forces smaller in the slaughterhouses with low pH values at 7 °C than in those
7 with the high ones.

8

9 It was concluded that a low cooling rate, or more specifically, the temperature/pH at the onset
10 of rigor mortis, is important for beef tenderness. The pH of LD must fall to values below 5.7
11 before/when the temperature reaches 7 °C.

12

13 *Keywords:* Cooling rate, pH, beef tenderness

1 **Introduction**

2

3 According to Miller et al., (1996) there are four main factors influencing the tenderness of
4 meat: 1) muscle shortening (the state of the actomyosin complex), 2) ageing (the action
5 enzymes [under longer period of time]), 3) the contents of connective tissue, and 4) marbling.
6 Toughness/tenderness is, however, much more complex (Dutson, review 1977; Greaser,
7 review 1986). There is increasing knowledge about the importance of the perimortal
8 phenomena which take place before the carcass has reached the ultimate temperature during
9 the cooling. The effects of calpains and their inhibitors immediately post mortem, all
10 depending on pH and temperature, have an influence on the tenderness (Dransfield,
11 review 1994; Koohmaraie, 1996). Also the time of excision of muscles (meat) from bones
12 should take place two days post mortem or later (Taylor and Richardson 1998).

13

14 The phenomenon 'cold shortening' or 'cold induced toughening' has been intensively studied
15 since the 1960s (Locker, 1985). The great majority of the studies has dealt with beef and
16 lamb, and to a much lesser extent with pork and poultry. Bendall (1973a) recommended that
17 a beef carcass should not be cooled to below 12 °C faster than in 15 h, i.e. before the
18 completion of rigor mortis. He had suggested earlier a rule of thumb "The temperature should
19 not be below 10 °C faster than in 10 h". Olsson, Herzman and Tornberg (1994) suggested the
20 temperature of 7 °C as the upper limit for cold shortening.

21

22 The susceptibility for cold shortening varies between animal species and between the muscle
23 types, predominantly red muscles being more susceptible than the white ones (Bendall,

1 1973a). Depending on the animal species and the location of the muscle, the time-temperature-
2 pH combinations are different in different muscles and also different in the different parts of
3 the same muscle. Puolanne and Ruusunen (1999) have also shown that in fixed muscle strips
4 the cold-induced shortening causes a lengthening of the sarcomeres in the warmer regions of
5 the muscle, especially in areas where the ATP consumption and consequently the rate of pH
6 fall are low (i.e. at about 15 °C). Consequently, tenderness as well as shortening may vary in
7 different parts of the muscle. Therefore, conclusions for the whole carcass must be more or
8 less arbitrary, which renders it impossible to give exact recommendations for cooling to obtain
9 tender meat in each part of the carcass. It seems, however, that cold shortening and cold
10 toughening are not the same thing, but they may be inter-related: when carcasses are cooled
11 quickly, they may or may not shorten and become tough. However, cold induced toughening
12 is not always connected with shortening, which suggests the importance of proteolytic factors.
13
14 There is some evidence that the pH value/temperature combinations at the onset of rigor
15 mortis are of importance. Bendall (1973a) reviewed studies of cold shortening. The rate of
16 ATPase activity decreases with decreasing temperature between 38-0 °C. It has also been
17 shown that the calcium binding capacity of the sarcoplasmic reticulum decreases strongly at
18 temperatures below 10 °C, if the pH value is lower than 6.6 (Kanda, Pearson and Merkel,
19 1977). The content of free P_i is also relevant: at low contents, when ATP is still regenerated,
20 the calcium retention is higher than close to the onset of rigor, when the P_i content is ten times
21 higher (Newbold and Tume, 1977). Honikel, Ronchalés and Hamm (1983) showed that
22 bovine *M. sternomandibularis* is able to shorten several times, when cooled to 0 °C, and relax
23 again, when warmed up to 20 °C. Bendall (1973a) showed that at 2 °C the cold shortening
24 creates in *M. longissimus dorsi* a work of 0.4 mJ/g, but the rigor shortening produces 3.1 mJ/g.

1 This means that the rigor shortening (formation of rigor) is far more important than the cold
2 shortening which takes place at higher pH values and ATP contents. In addition, the
3 formation of rigor mortis at low temperatures is more likely, in relation to the whole muscle
4 mass, than cold shortening that takes place usually only in the surface areas of the muscles of
5 beef carcasses. Finally, cooling regimes that cause cold shortening may later also cause cold
6 toughening due to rigor shortening, unless the temperatures are not elevated during the later
7 periods of cooling, as is done in some industrial practices (unpublished information from
8 slaughterhouses). The content of free calcium is very much based on the temperature and to a
9 lesser degree on the pH value (Kanda, Pearson & Merkel, 1977)

10

11 Goll, Geesink, Taylor and Thompson (1995) have presented a hypothesis that a shortening as
12 such does not cause the toughening, but it is caused by the circumstances prevailing during the
13 shortening. Locker and Daines (1976) moved beef muscles cooled 48h at 2 °C but still in pre
14 rigor state, to 37 °C and cooled them again after the onset of rigor. The treatment caused a
15 shortening of 30% compared to muscles kept at 15 °C at rigor, but the meat was more tender
16 than muscles kept all the time at 2 °C. According to Koohmaraie (review 1996) this is due to
17 the effects of different activities of proteolytic enzymes. Lochner, Kauffman and Marsh
18 (1980), Heinze, Naudé and van Rensburg (1986), Dransfield, Wakefield and Parkman (1992),
19 Olsson, Herzman and Tornberg (1994) and Bekken, Berg, Frøystein and Hildrum (1996) have
20 also shown that low temperatures at the end of the cooling cause a marked toughening of
21 meat, irrespective of the degree of (cold) shortening.

22

23 Based on the studies cited above it was assumed that the cooling regime should be selected
24 based on the pH-temperature course of the carcass, especially in those muscles that are usually

1 used as whole meat meals, such as steaks etc. To test the hypothesis formulated on the basis of
2 laboratory type studies we selected seven beef slaughterhouse with different cooling regimes
3 and measured the relationship between the rates of pH-fall and temperature fall, and
4 tenderness.

5

6 **Materials and methods**

7

8 *Selection of the study material.* Before the study all approved industrial beef slaughterhouses
9 in Finland (14) were questioned about their cooling regimes. On the basis of the interviews, 7
10 slaughterhouses which were most different from each other were selected for further studies.
11 Because the confidentiality of the interviews the details of the cooling system are not given,
12 except the cooling rate (Table 1).

13

14 *Samples.* In each of the selected seven slaughterhouses, 8-20 bull carcasses (in total 100) were
15 studied for their pH and temperature fall. The age of bulls was 18-20 months and the carcass
16 weight was on average 259 kg (standard deviation 38 kg). The temperature and pH
17 measurements were made from *M. longissimus dorsi* by the 13th vertebra and in *M.*
18 *semimembranosus* caudally above the pelvis (*Os coxae*).

19

20 Eight carcasses from each slaughterhouse were selected for tenderness measurements. From
21 each carcass *longissimus dorsi* and *semimembranosus* muscles were removed, vacuum
22 packaged and kept at 3-4 °C for 5 or 21 days. pH and temperature measurements were done
23 from the other side, and the intact muscles from the other side were used for tenderness

1 measurements. No muscles having a pH_u higher than 5.80 were included. After a storage
2 period of 5 days, packages were opened and the samples were cut into two parts. One half
3 was used for tenderness measurements (shear force measurements and sensory evaluation),
4 and the other half was vacuum packaged again and kept for another 16 days for respective
5 analysis.

6

7 *Temperature.* The temperatures of the carcasses during cooling were measured by a KM 25
8 Foodcheck Thermometer (Comarck Ltd, England). The probe was adjusted to penetrate 40
9 mm deep from the surface. The first measurement was made at the time of weighing (time
10 0.00) which took place about 40 minutes after stunning. The measurements were repeated at
11 every 2 ... 8 hours (in the beginning more frequently than in the end of the period) until about
12 30 hours, when the cooling was completed and carcasses moved to a storage room.

13

14 *pH-value.* The samples for pH measurements were taken, at the same time when also the
15 temperature was measured, with a biopsy needle from a depth of 40 mm, close to the point
16 where the temperature reading was obtained. The sample (about 0.1 g) was inserted into a 1.5
17 ml Eppendorf tube with 0.9 ml sodium iodine acetate (5 mmol/l Na-I acetate and 150 mmol/l
18 KCl; Bendall, 1973b). The muscle sample was disrupted with a glass rod. The pH was
19 measured by Knick Portamess 752 Calimatic pH meter (Knick Elektronische Meßgeräte
20 GmbH, Germany) with Xerolyte Inlab 427 electrode.

21

22 *Testing the shear force measurement.* The correlation between sensory evaluations and Allo-
23 Kramer/Instron measurements was tested (Smith, Lyon and Fletcher, 1988). Previously in our
24 laboratory Warner-Bratzler shear force has been used for beef, but the Allo-Kramer method

1 for poultry. A panel of 9 experienced persons evaluated the tenderness of (method described
2 below) *M. longissimus dorsi*, *semimembranosus*, *semitendinosus* and *infraspinatus*, after
3 ageing for 21 days. The total correlation between means of the sensory evaluations and Allo-
4 Kramer/Instron measurements was 0.96, and the correlations between the means within the
5 individual muscles ranged from 0.70 (*M. infraspinatus*) to 0.99 (*M. semimembranosus*).

6

7 *Shear force measurements.* Muscle samples were cut into 30 mm thick pieces across the fibre
8 axis. The samples were packaged individually into small vacuum packages. They were
9 cooled to 4 °C and then cooked for 26 minutes at 80 °C to reach a core temperature of 71-75
10 °C and then cooled to 4 °C (AMSA, 1995). The shear force measurements were made by
11 Instron Model 6625 (Instron Co, USA). The shear force measurements and sensory
12 evaluations were performed within four days.

13

14 From the cooked samples 4-6 pieces of 30 mm *10 mm * thickness of the sample (before
15 cooking 30 mm) were cut. The pieces were weighed and then placed on an Allo-Kramer shear
16 shell and cut across the fibre axis. The results are given in Newtons/g cooked sample.

17

18 *Sensory evaluation.* About 6 mm thick samples, cut across the fibre axis, were given to the
19 panel members. The 11 panel members were experts in the evaluating of meat tenderness.

20 There were first 6 training sessions and then 28 sample sessions. For each session 2*4
21 samples were evaluated. The tenderness was rated on graphical intensity scale. The

22 evaluation form was a 140 mm long line, anchored at both ends (0=tough ... 140=tender).

23 The assessors were asked to put a mark on the spot as she/he evaluated the sample.

24

1 *Statistical analysis.* The data were treated with Microsoft Excel 97 and tested with
2 Statsgraphic Plus 3.0. One-way analysis of variance, least significant differences and
3 regression equations were calculated.

4

5 ***Results and discussion***

6

7 The pH-temperature curves of different carcasses in the same slaughterhouse were very
8 different during cooling (data not shown). Several different cooling rate/pH indicator values
9 were calculated on the basis of the primary data, but only the pH-temperature combination that
10 gave the best fit (the highest correlation with shear force) is reported. It was possible to find
11 significant differences in time/temperature curves and in pH values between the
12 slaughterhouses as shown in Table 1. *M. semimembranosus* cooled slower than *M.*
13 *longissimus dorsi*, and therefore indicator values are given for both muscles.

14

15 The average time to reach 20 °C in *M. semimembranosus* was 7 h 20 minutes, and there was a
16 significant difference between the slaughterhouses ($p < 0.001$; Table 1). The shortest time to
17 cool to 20 °C was 5 h 56 min, and the longest 9 h 41 min. The lowest temperature by 24 h
18 were in 4 °C and the highest 10 °C, respectively, differing significantly between the
19 slaughterhouses ($p < 0.05$). When the temperature was 20 °C, the pH of individual muscles
20 varied between 5.46 - 6.05.

21

22 The average time to reach 10 °C in *M. longissimus dorsi* was 7 h 45 min (4 h 25 min - 10 h 24
23 min. Five of seven slaughterhouses differed from each other ($p < 0.05$). When the temperature

1 was 7 °C, the pH was on average 5.89 and varied between 5.52 - 6.17. The slaughterhouses
2 formed three different groups, based on the pH at 7 ° C (p< 0.05; Table 1). In some
3 slaughterhouses the pH was close to the pH_u, but in some others only about a half of the pH
4 fall had taken place.

5

6 During that period the shear forces decreased 18% (*M. longissimus dorsi*) and 8% (*M.*
7 *semimembranosus*). By sensory evaluation the tenderness increased 24% and 0%,
8 respectively. (Results not shown).

9

10 Because the correlations between shear force measurements and sensory evaluation within the
11 slaughterhouses were on average -0.85 ranging from -0.78 to -0.85 for *M. longissimus dorsi*,
12 only the shear force measurements are discussed later. In *M. semimembranosus* the changes
13 were smaller and the correlations were lower, being -0.69 on average, and none or hardly any
14 tenderisation was found by ageing. Therefore, *M. semimembranosus* will not be discussed any
15 further below.

16

17 The correlations between the shear force measurements and different cooling rate/pH indicator
18 values were calculated to find the best fit. It was found that the pH value of meat when the
19 temperature reached 7 °C was the most significant factor to explain the shear force. The
20 correlation between the pH values at 7 °C and shear force values, using the slaughterhouse
21 averages, by 5 days *post mortem* was $r=+0.94$ ($p=0.002$). The regression equation ($N = 7$, R^2
22 = 87.1%) was (Equation (1); Figure 1):

23

24 $LD5SF = -295.4 + 73.0 * pH-7^{\circ}C$, where (1)

1

2 LD5SF = shear force of *M. longissimus dorsi* at 5 days *post mortem*

3 pH-7°C = the pH value when the temperature reached 7 °C.

4

5 By 21 days *post mortem* the respective values were $r = +0.84$ ($p = 0.017$) and for the regression

6 equation $R^2 = 71.0\%$ ($N = 7$). If the correlations ($r = 0.50$; $p = 0.0002$) were calculated by

7 individual carcasses, the equation was $LD5SF = -124.3 + 43.8 * pH-7^\circ C$ ($N = 56$, $R^2 =$

8 25.0%). The results that are based on the slaughterhouse averages are practically more

9 important, because the cooling process cannot be controlled for individual carcasses.

10

11 According to the results of sensory analysis and the comments of the assessors, it was

12 concluded that the shear force values over 120 N/g represent very tough meat and values

13 below 100 N/g tender meat. The shear force results for *M. longissimus dorsi* of the individual

14 carcasses are given in Figure 2. for 5 days *post mortem* and in Figure 3. for 21 days,

15 respectively. Slaughterhouses are put in the order of ascending mean pH-7°C values. It can

16 be seen that not only the *longissimus dorsi* muscles from slaughterhouses with a low pH-7°C

17 value are on average tender, but also the variation is lower. Most *longissimus dorsi* muscles in

18 slaughterhouses E and F are not tough at 5 d *post mortem*, and all shear force values were

19 below 120 N/g level by 21 d *post mortem*. On the contrary, meat from slaughterhouses with

20 high pH-7°C values (G, D, B and A) are mostly very tough and the variation is about twice so

21 high as in low pH-7°C values (E and F). In addition, in *longissimus dorsi* muscles of

22 slaughterhouses of lower pH-7°C values (E, F and C) a clear tenderising effect of ageing can

23 be seen, but in higher pH-7°C values the high variation in tenderness remained, and especially

24 the toughest samples did not become more tender with ageing.

1

2 It seems that the pH should be 5.7 or below when the temperature reaches 7 °C. The results
3 also suggest that the pH value/temperature relate to the formation of rigor. If the cooling is
4 first fast but then slowed down to allow the pH to fall and rigor to set, the meat still is tender.
5 The results clearly confirm the laboratory scale findings of Lochner, Kauffman and Marsh
6 (1980), Heinze, Naudé and van Rensburg (1986) Dransfield, Wakefield and Parkman (1992),
7 Olsson et al. (1994), Bekken et al. (1996) and Goll, Boehm, Geesink, and Thompson (1997).
8 Dransfield (review 1998) made a very similar conclusion based on his studies with meat
9 cooled to 0 °C then kept in 15 °C until the rigor. Also when studying water-binding of pork,
10 Puolanne and Turkki (1983) showed that there is a point of discontinuity in the pH-water-
11 binding curve at about pH 5.85. Further studies on rigor formation are warranted, whether the
12 rigor is different, as Goll et al. (review 1995) pointed out, when formed at different pH-
13 temperature combinations.

14

15 The authors want to stress that it is of utmost importance that the pH value and temperature
16 are determined at the moment when rigor mortis commences. The temperature course before
17 that point is not relevant, provided that the pH is not too high when the temperature reaches 7
18 °C. Our preliminary tests (under preparation) even showed that it was possible to lower the
19 temperature temporarily to low values (3.5 °C) provided that the temperature is elevated to 10
20 °C for the time period when the rigor begins, i.e. in normal meat at pH values 5.7-5.8.

21

22 It should be noted, however, that pH and temperature have many effects on *post mortem*
23 proteolysis, Ca-binding, water-binding etc, and therefore the phenomena studied here are not
24 the only *post mortem* factors affecting the tenderness of meat. Electrical stimulation can be

1 used to increase the rate of the pH fall, but this will not necessarily produce more tender meat
2 by very fast chilling of all muscles, although the pH is low before low temperatures have been
3 reached. Tenderness would further benefit if the carcass are not cut before 48 h p.m.
4 (Eikelenboom and Smulders, 1998; Taylor and Richardson, 1998). - All evidence points to the
5 fact that there is no single factor explaining/controlling the tenderness of meat.

6

7 It can be concluded that when beef carcasses are cooled very fast to reduce the proliferation of
8 harmful surface microbes, the meat seems to be more tender and the ageing more effective if
9 the carcasses are kept at elevated (meat) temperatures (above 7-10 °C) until the onset of rigor,
10 i.e. pH 5.7. The pH-temperature relationship at the moment of the onset of rigor is the
11 decisive factor. The tenderness of all muscles of the carcasses cannot be controlled by the
12 same cooling regime.

13

14 **References**

15 AMSA (1995). Research guidelines for cookery, sensory evaluation and instrumental
16 tenderness of fresh meat. American Meat Science Association, Chicago.

17 Bekken, K. E., Berg, J., Frøystein, T. & Hildrum, K. I. (1996). Susceptibility of individual
18 beef carcasses to toughening by different chilling regimes. *Proceedings of the 42nd*
19 *International Congress of Meat Science and Technology* (pp. 392-393). Den Haag,
20 Holland.

21 Bendall, J. R. (1973a). The biochemistry of rigor mortis and cold-contraction. *Proceedings of*
22 *the 19th European Meeting of Meat research Workers* (pp 1-27). Paris, France.

1 Bendall, J. R. (1973b). Post mortem changes in muscle. In G. H. Bourne (ed.) *Structure and*
2 *Function of Muscle* (pp 244-309). London and New York: Academic Press.

3 Dransfield, E. (1994). Optimisation of tenderisation, ageing and tenderness. *Meat Science*,
4 36, 105-121.

5 Dransfield, E. (1998). Texture in very fast chilled beef. In: Dransfield, E & Ronchalés, P.
6 (ed.): *Very Fast Chilling in Beef, 2. Muscle to Meat* (pp. 17-22). EU Concerted Action
7 CT94-1881. University Bristol Press, Bristol, United Kingdom.

8 Dransfield, E., Wakefield, D. K. & Parkman, I. D. (1992). Modelling post-mortem
9 tenderisation - 1: Texture of electrically stimulated and non-stimulated beef. *Meat Science*,
10 31, 57-73.

11 Dutson, T.R. (1977) Rigor onset before chilling. *Proceedings of the 30th Annual Reciprocal*
12 *Meat Conference* (pp. 79-86).

13 Eikelenboom, G. & Smulders, F. J. (1998) Research on electrical stimulation in the
14 Netherlands. In: Dransfield, E & Ronchalés, P. (ed.): *Very Fast Chilling in Beef, 2. Muscle*
15 *to Meat* (pp. 49-54). EU Concerted Action CT94-1881. University Bristol Press, Bristol,
16 United Kingdom.

17 Goll, D. E. , Boehm, M. L., Geesink, R. G. & Thompson, V. F. (1997). What causes
18 postmortem tenderization. *Proceedings of the 50th Annual Reciprocal Meat Conference*
19 (pp. 60-67).

20 Goll, D. E., Geesink, R. G., Taylor, R. G. & Thompson, V. F. (1995). Does proteolysis cause
21 all postmortem tenderization, or are other changes in the actin/myosin interaction involved?
22 *Proceedings of the 41st International Congress of Meat Science and Technology* (pp. 537-
23 544). San Antonio, USA.

- 1 Greaser, M.L. (1986) Conversion of muscle to meat. In : *Muscle as Food*, ed. P.J. Bechtel,
2 Academic Press, NY. (pp. 37-94).
- 3 Heinze, P. H., Naudé, R. T. van Rensburg, A. J. (1986). The effect of chilling temperature
4 and carcass mass on meat tenderness. *Proceedings of 32nd European Meeting of Meat*
5 *Research Workers* (pp. 95-98). Ghent, Belgium.
- 6 Honikel, K.O., Ronchalés, P. & Hamm, R. (1983). The influence of temperature on
7 shortening and rigor onset in beef muscle. *Meat Science*, 8, 221-241.
- 8 Kanda, T., Pearson, A. M. & Merkel, R. A. (1977). Influence of pH and temperature upon
9 calcium accumulation and release by bovine sarcoplasmic reticulum. *Food Chemistry*, 2,
10 253-266.
- 11 Koohmaraie, M. 1996. Biochemical factors regulating the toughening and tenderization
12 processes of meat. *Meat Science*, 43, 193-201.
- 13 Lochner, J. V., Kauffman, R. G. Marsh. B. B. (1980). Early-post-mortem cooling rate. *Meat*
14 *Science*, 4, 227-241.
- 15 Locker, R. H. (1985) Cold-induced toughness of meat. In *Advances in Meat Research* Vol. 1 -
16 Electric Stimulation, eds Pearson, A.M. & Dutson, T. R. AVI Publishing Co. Inc.
17 Westport, CT (pp. 1-44).
- 18 Locker, R.H. & Daines, G. J. (1976). Tenderness in relation to the temperature of *rigor* onset
19 in cold shortened beef. *Journal of the Science of Food and Agriculture*, 27, 193-196.
- 20 Miller, R. K., Taylor, J. F., Sanders, J. O., Lunt, D. K., Davis, S. K., Turner, J. W., Sawell, J.
21 W., Kallel, F., Ophir, J. & Lacey, R. E. (1997). *Proceedings of the 49th Annual Reciprocal*
22 *Meat Research Conference* (pp. 106-113).

- 1 Newbolt, R. B. (1980). Update: calcium uptake and release by skeletal muscle mitochondria
2 and sarcoplasmic reticulum. *Proceedings of the 32nd Annual Reciprocal Meat Conference*
3 (pp 70-78). Brooking, South Dakota, USA.
- 4 Newbolt, R. B. & Tume, R. K. (1977). Effect of ortophosphate and oxalate on the cold
5 induced release of calcium from sarcoplasmic reticulum preparations from rabbit skeletal
6 muscle. *Australian Biological Sciences*, 30, 519. Ref. Newbold, 1980.
- 7 Olsson, U., Herzman, C. & Tornberg, E. (1994). The influence of low temperature, type of
8 muscle and electrical stimulation on the course of rigor mortis, ageing and tenderness on
9 beef muscles. *Meat Science*, 37, 115-131.
- 10 Puolanne, E. & Ruusunen, M. (1998). Effect of linear temperature gradient on sarcomere
11 length in pre-rigor meat strips. In: Dransfield, E & Ronchalés, P. (ed.): *Very Fast Chilling*
12 *in Beef, 2. Muscle to Meat* (pp. 31-36). EU Concerted Action CT94-1881. University
13 Bristol Press, Bristol, United Kingdom.
- 14 Puolanne, E. & Turkki, P. (1983). Effect of pre-rigor salting on the water-binding capacity of
15 pork. *Proceedings of the 29th Meeting of Meat Research Workers* (pp. 352-357). Parma,
16 Italy.
- 17 Smith, D. P., Lyon, C. E. & Fletcher, D. L. (1988). Comparison of the Allo-Kramer shear and
18 texture profile methods of broiler breast meat texture analysis. *Poultry Science*, 76, 1549-
19 1556.
- 20 Takahashi, K. (1999). Mechanism of meat tenderization during post-mortem ageing:
21 Calcium theory. *Proceedings of the 46th International Congress of Meat Science and*
22 *Technology* (pp. 230-235). Yokohama, Japan.
- 23 Taylor, A. A. & Richardson, R. I. (1998). Research on electrical stimulation in UK. In
24 Taylor, A. A. & Richardson, R. I. (ed.): *Very Fast Chilling in Beef, 3. Eating Quality* (pp.

- 1 11-17). EU Concerted Action CT94-1881. University Bristol Press, Bristol, United
- 2 Kingdom.

1 Table 1. The slaughterhouse mean durations of temperature fall to 20 °C and 10 ° C(cooling
 2 time, h), pH values and 5-day shear forces (N/g) of muscles in seven slaughterhouses. N=8
 3 carcasses/slaughterhouse

Slaughterhouse	<i>M. semimembranosus</i>			<i>M. longissimus dorsi</i>		
	Cooling time to 20 °C (h)	pH at 20 °C	5-d shear force (N/g)	Cooling time to 10 °C (h)	pH at 7 °C	5-d shear force (N/g)
A	5.56 ^a	5.84 ^c	122 ^{ab}	4.25 ^a	6.16 ^c	155 ^c
x	0.54	0.19	10.4	0.56	0.14	22.6
B	6.21 ^{ab}	5.79 ^{bc}	166 ^c	8.04 ^c	5.97 ^b	153 ^c
	0.50	0.21	38.1	1.08	0.19	18.0
C	8.51 ^d	5.86 ^c	125 ^{ab}	10.24 ^e	5.84 ^b	126 ^{ab}
	1.06	0.17	15.0	1.54	0.17	18.1
D	7.27 ^c	6.05 ^d	132 ^b	7.42 ^{bc}	6.17 ^c	152 ^c
	1.04	0.16	18.1	1.11	0.19	18.0
E	7.10 ^{bc}	5.46 ^a	109 ^a	7.33 ^{bc}	5.52 ^a	108 ^a
	0.50	0.05	19.0	0.55	0.08	12.7

1	F	6.13 ^a	5.68 ^b	127 ^{ab}	6.59 ^b	5.63 ^a	116 ^{ab}
2		0.34	0.15	11.7	0.53	0.15	11.7
3							
4	G	9.41 ^e	5.74 ^{bc}	130 ^{ab}	9.09 ^d	5.95 ^b	130 ^b
5		1.28	0.20	24.2	1.08	0.23	24.2
6							

7 ^{a...e)} Values with the same letter within a column are not significantly different (P>0.05)

8 x mean

9 s standard deviation

1 Figure 1. The regression line between the mean values of shear force and pH at 7 °C in
2 slaughterhouses A...F. N=8/slaughterhouse. $R^2= 87.1$. LD5SF = shear force of *M. longissimus*
3 *dorsi* at 5 days *post mortem*; pH-7°C = the pH value when the temperature reached 7 °C.

4

5

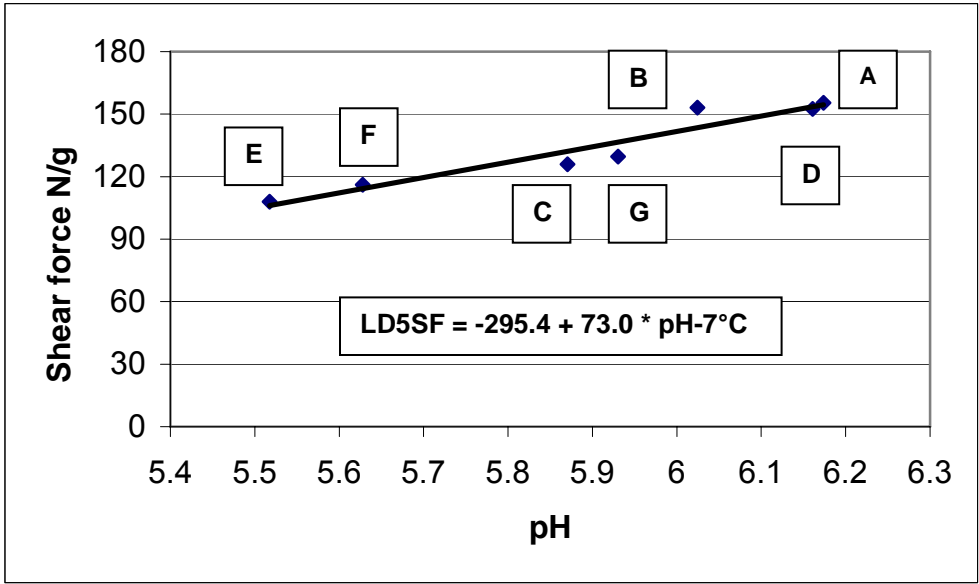
6 Figure 2. Shear forces of individual *M. longissimus dorsi* muscles in slaughterhouses in
7 ascending order, at 5 d post mortem. Broken line = the mean of all samples.

8

9 Figure 3. Shear forces of individual *M. longissimus dorsi* muscles in slaughterhouses in
10 ascending order, at 21 d post mortem. Dotted line = the mean of all samples at 5 d post
11 mortem, broken line = 21 d post mortem.

1 **Figure 1**

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1 **Figure 2**

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1 **Figure 3**

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