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Effects of Thermal Processing Combined with High Pressure on the Characteristics of Cooked Pork

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초고압 열처리가 가열 돈육의 품질특성에 미치는 효과

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Abstract

This study evaluated the effects of thermal processing combined with high pressure on the properties of cooked pork. Pressurization followed by heating (PFH), heating followed by pressurization (HFP) and heating under pressurization (HUP) treatments were compared to a heated only control. Cooked meat without simultaneous pressurization showed little or no decrease in water binding properties relative to the control, regardless of the sequence of pressurization and heating. However, HUP treated pork had significantly higher water binding properties than the control ($p<0.05$). The pH values of all treatments were not significantly different with the exception of HUP at 300 MPa. The HUP treated pork showed the best tenderizing effects among all the treatments tested and the effect was more significant at increased pressure levels ($p<0.05$). In addition, increasing pressure levels significantly increased the L-values of pork ($p<0.05$). PFH and HFP treated pork had significantly lower a-values ($p<0.05$), while no significant differences were observed in HUP. HUP treated pork had the lowest b-values at 100 MPa, however, the differences were not significant at increasing pressure levels. These results indicate that heating under pressure is the best cooking condition for improving the quality characteristics of pork without adversely affecting its appearance.

Key words : high pressure, heating, pork, cookery, eating quality

Introduction

During the past 10 years, high pressure has become a new parameter in food processing. Three domains of food processing are of potential interest with regard to high pressure, including food texture, preservation and phase change (Cheftel, 1995; Knorr *et al.*, 1998).

Since the tenderization of meat by high pressure was first proposed by Macfarlane (1973) on pre-rigor meat, numerous investigations on pre-rigor meat have been published (Horgan, 1979; Koohmaraie *et al.*, 1984; Suzuki *et al.*, 2001). However, the application of high pressure during the pre-rigor period is difficult to perform because this requires hot-boning, which is not widely used in industry, as well as pressurizing the muscle when the pH is high, i.e., during a short period of time that can vary from one muscle to another depending on rigor onset (Cheftel and Culioli, 1997).

Therefore, more recent investigations have examined meat treatment after the completion of rigor. In principle, the post-mortem tenderization of meat results from changes in the muscle during aging, i.e., weakening of actin-myosin interactions, fragmentation of myofibrils into short segments due to Z-line disintegration, degradation of the elastic filaments consisting of connectin, and the weakening of connective tissue (Suzuki *et al.*, 1996). However, the effects of pressure on the post-mortem muscle during meat tenderization are still not clear. In general, pressure up to 300 MPa has no effect on connective tissue, and the pressure-induced tenderization of meat is most likely caused only by the reduction

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of actomyosin toughness attributed to the myofibrillar protein (Suzuki *et al.*, 1993). Macfarlane *et al.* (1981) examined the shear values of post-rigor bovine muscle pressurized at 150 MPa for 3 hr at 0°C and reported that pressure treatment did not change shear values when the muscle was in a stretched or contracted state. According to our previous studies (Hong *et al.*, 2005; Ko *et al.*, 2006; Hong *et al.*, 2007), pressurization of post-rigor pork at ambient temperature had no effect on tenderness, while pressurization at subzero temperature increased the shear value of pork by increasing either the pressure level or holding time.

In contrast to our previous results, Bouton *et al.* (1977a) reported that 100 MPa of pressure applied for 2.5 min or longer to post-rigor muscle heated to 40-60°C improved the tenderness of the meat when subsequently cooked. Locker and Wild (1984) also reported that pressure-heat treatment tenderized post-rigor muscle after a considerable period of time at an elevated temperature.

According to our preliminary studies, pressurization at an elevated temperature did not have any beneficial effects on tenderness and the meat was still tough at increased pressures or temperatures. This discrepancy may be due to the sequence of the pressure and thermal treatments. Thus, these results indicate that the pressure-induced tenderization of post-rigor meat requires a subsequent heat treatment. Therefore, this study was aimed at evaluating the effects of pressure level and the sequence of pressure and heat treatments on the characteristics of cooked pork.

Materials and Methods

Sample Preparation

Porcine *m. longissimus dorsi* samples at pH 5.4-5.6 were randomly selected from 6 carcasses at 24 hr post-mortem from three different commercial markets. For each treatment, 120 cylindrical samples approximately 20 mm in diameter and 80 mm in length were cut from the center of the muscle with their axis parallel to the fiber direction and vacuum sealed in a polyethylene pouch.

Heat and Pressure Treatment

High pressure treatments were performed in a vessel as described previously (Hong *et al.*, 2005). Ethanol was used as the pressure transmitting medium. Compression and depression rates were 2.4 and 23 MPa/s, respectively. A thermocouple (k-type) was inserted into the center of the sample and the temperature was monitored using a mobile recorder (MV 104, Yokogawa Co., Osaka, Japan). For heating under pressure treatment (HUP), samples were placed in a vessel that was maintained at 20°C. After reaching the targeted pressure level, the temperature was increased to 80°C by circulating 90°C water around the vessels. The pressure was released after 30 min when the meat temperature reached 75°C (Fig. 1). The total pressure holding time was 100 min. For pressure followed by heating (PFH), all samples were pressurized at the targeted level for 100 min and then heated to 75°C and kept at this temperature for 30 min. For heating followed by pressurization (HFP), the meat was heated at 75°C for 30 min and then pressurized at the targeted level for 100 min at 10°C. The non-pressurized control (C) was heated to 75°C and kept at this temperature for 30 min. All treatments were cooled with running tap water for 15 min and tempered at ambient temperature for 30 min.

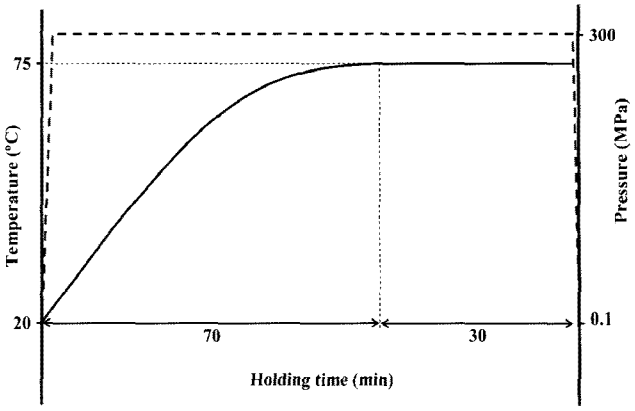

Fig. 1. Example of the schematic procedure for heating pork under pressurization at 300 MPa. Solid and dashed lines present temperature of sample and pressure level, respectively.

Water Binding Properties

The cooking loss was determined by assessing the value of exudation after thermal treatment. All samples were weighed before and after treatment, and the cooking loss was expressed as a percentage of the initial weight. The water holding capacity (WHC) was determined by the method of Hong *et al.* (2005) with some modification. The moisture contents of the meat before (M_1) and after treatment (M_2) were determined using the 102°C drying method. The WHC was expressed as the percentage of remaining moisture in the meat as follows:

$$\text{Water holding capacity (\%)} = \left(1-\frac{M_1-M_2}{M_1}\right)\times 100$$

pH

The pH measurements were carried out with a pH meter (pH900, Precisa Co., Dietikon, Swiss) on 5 g of sample mixed with 20 mL of distilled water and homogenized at

13,000 rpm for 1 min in a homogenizer (SMT Process Homogenizer, SMT Co. Ltd., Tokyo, Japan).

Shear Force

Samples that were 10 mm in diameter and 50 mm in length were cut parallel to the longitudinal orientation of the muscle fiber. Each strip was sheared using a digital gauge (DPS-20, IMADA Co., Toyohashi, Japan) and the average shear force was calculated. Head speed was maintained at 60 mm/min and the analysis was conducted at least 24 times.

Color Measurement

Color measurements were taken with a color reader (CR-10, Konica Minolta Sensing Inc., Tokyo, Japan) calibrated with a white standard plate (L = +97.83, a = -0.43, b = +1.98). CIE L, a and b values were determined and used as indicators of lightness, redness and yellowness, respectively. Six measurements were taken from each surface of the samples.

Statistical Analysis

The data were analyzed by one-way ANOVA using the SAS statistical program 9.1 (SAS Institute, Cary, USA). Differences among the means were compared using Duncan's multiple range test.

Results and Discussion

Water Binding Properties

The water binding properties of pressure-heat treated pork samples are given in Table 1. For PFH and HFP treated pork, increasing the pressure level tended to increase the cooking loss. Significant differences in cooking loss were observed at 100 and 300 MPa in PFH and HFP treatments, respectively ($p<0.05$). However, the cooking loss with HUP treatment was significantly lower than that of the control ($p<0.05$). The lowest cooking loss with HUP treatment was at 100 Mpa, and cooking loss significantly increased at increasing pressure levels ($p<0.05$). A similar result was also obtained for the water holding capacity (WHC). With regard to WHC, the pressure level had no effect in PFH and HFP treatments. However, the WHC in the HUP treatment was significantly higher than the control ($p<0.05$).

Bouton *et al.* (1977b) also reported less moisture loss for pressure-heat treated beef compared to beef that was thermally treated. The author postulated that moisture was lost from the samples during the pressure-heat treatment so it was to be expected that less moisture would be lost from these samples during cooking. However, the pressure-heat treated meat was also cooked again after treatment. In that study, beef subjected to HUP treatment was cooked only during pressurization. Therefore, the improved water binding properties observed during HUP treatment may be due to pressure induced changes in the meat proteins. This phenomenon was most likely due to the conformational changes in the meat proteins caused by pressurization, particularly protein dissociation.

Table 1. Effects of pressure levels and pressurization and heating procedures on the water binding properties of pork[1)]

Pressure (MPa)	Treatments[2)]		
	PFH	HFP	HUP
Cooking loss (%)			
C[3)]	27.51±0.80^{Bx}	27.51±0.80^{Bx}	27.51±0.80^{Ax}
100	32.38±0.94^{Ax}	28.05±0.82^{By}	16.15±0.47^{Dz}
200	32.75±0.95^{Ax}	28.93±0.84^{By}	17.52±0.51^{Cz}
300	33.35±0.97^{Ax}	32.99±0.96^{Ax}	23.28±0.68^{By}
Water-holding capacity (%)			
C	88.51±0.81^{Ax}	88.51±0.81^{Ax}	88.51±0.81^{Bx}
100	88.88±0.53^{Az}	90.96±1.34^{Ay}	95.38±0.87^{Ax}
200	91.89±3.72^{Ax}	89.79±3.51^{Ax}	96.14±1.47^{Ax}
300	88.21±0.49^{Ay}	89.39±1.62^{Ay}	94.84±0.84^{Ax}

[1)] Mean±SD from triplicate determinations.
[2)] PFH, pressurization followed by heating; HFP, heating followed by pressurization; HUP, heating under pressurization.
[3)] C, heated and non-pressurized control.
[A-D] Means with different superscripts within the same column are significantly different ($p<0.05$).
[x-z] Means with different superscripts within the same row are significantly different ($p<0.05$).

According to Macfarlane (1985), pressure acts by disrupting divalent cation-protein bonds through an electrostriction effect. Upon pressure release, the probability of salt bridges reforming is reduced because of changes in protein conformation which occurred during the applied pressure treatment. As a result, increases in the water binding properties and protein solubility could persist after pressure release. In addition, subsequent applied heat treatment results in effective gelation of the meat proteins, especially myosin, which would result in higher moisture retention after treatment since this protein acts as the major gel forming protein in meat (Thawatchai and Apichartsrangkoon, 2007). In general, pressurization conditions determine what gelation model was induced during heating (Carballo *et al.*, 2001). According to Carballo *et al.* (2001), pressurization at non-denaturing temperatures causes some alterations in protein conformation, which favors protein-protein interactions during heating and hence retains more moisture in its matrix. Pressurization during PFH treatment, on the other hand, can also improve the water binding properties as described

above. However, moisture was lost after atmospheric heating, which resulted in a higher cooking loss than the control since aggregated meat proteins could not bind with moisture. In addition, cooked meat at atmospheric pressure also results in protein aggregation and posterior applied pressure had no effect on the protein-water interaction. Consequently heating under pressurization could maintain a higher quality of moistness in the meat.

pH

The changes in pH of pork after pressure-heat treatments are given in Fig. 2. The pH values of all samples ranged from 5.88 to 6.04. For PFH and HFP treatments, the sample pH was not affected by the applied pressure level. The sample pH after HUP treatment up to 200 MPa also showed no significant differences relative to the control ($p>0.05$), while significantly high pH was obtained at 300 MPa during HUP treatment ($p<0.05$). Ma and Ledward (2004), who investigated the effects of temperature and pressure level on beef muscle, reported an increased pH with increasing pressure and temperature. The authors concluded that, although pressure and temperature both lead to small but significant increases in pH, the effects are not additive and that, even though the structures established by pressure and heat treatment may differ, the burying of acidic groups is similar in both cases. However, they compared pressure-heat treated meat with raw controls.

As reviewed by Knorr *et al.* (2006), when differences in protein structure were found, the conformational changes in proteins that occurred under high pressure were analogous to those under high temperature. They reported that temperature and chemical-induced protein denaturation often irreversibly unfold the complete protein because of covalent bond breakage and molecule aggregation. In contrast, pressurization can leave parts of the molecule unchanged, indicating that the denaturation mechanisms are substantially different. In aqueous solution, pressure affects mainly the tertiary and quaternary structure of proteins. Covalent bonds are rarely affected by pressurization, and even α-helix or β-sheet structures appear to be almost incompressible (Balny and Masson, 1993; Heremans and Smeller, 1998; Knorr *et al.*, 2006). In contrast to temperature, which destabilizes the protein molecules by transferring non-polar hydrocarbons from the hydrophobic core towards the aqueous exterior, pressure denaturation is initiated by forcing water into the interior of the protein matrix. A loss of contact between groups in the non-polar domains can cause unfolding of parts of the protein molecules. Hence, the stability of a protein under high pressure conditions is largely affected by its conformational flexibility to compensate losses of non-covalent bonds due to the relocation of water molecules (Priev *et al.*, 1996; Smeller, 2002; Boonyaratanakornkit *et al.*, 2002; Knorr *et al.*, 2006).

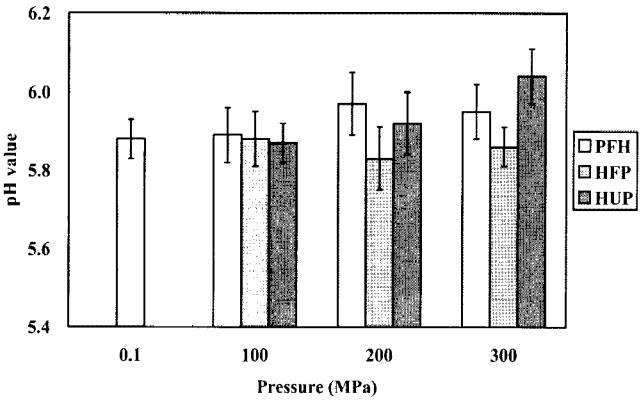

Fig. 2. Effects of pressure levels and pressurization and heating procedures on the pH of pork. PFH, HFP, and HUP represent pressurization followed by heating, heating followed by pressurization and heating under pressurization, respectively.

As a result of water penetration into the protein interior, pressure is likely to lead to conformational transitions, resulting in protein unfolding (Saad-Nehme *et al.*, 2002; Knorr *et al.*, 2006). As a result of protein unfolding, meat pH could potentially increase. However, Ma and Ledward (2004) pressurized the beef meat for only 20 min at 70°C. According to Hong *et al.* (2005), the pH of pork pressurized at 100 MPa significantly changed up to 30 min and then no changes were reported. Therefore, no differences in pH among treatments or pressure level in the current study could have resulted from longer pressure holding time (100 min) and heating at higher temperature (75°C).

Shear Force

Table 2 presents the effects of pressure-heat treatments on the shear force of pork. Increasing the pressure level in PFH and HFP treatments significantly increased the shear force of pork ($p<0.05$), while a significant decrease in shear force was observed with HUP treatment ($p<0.05$). In addition, HFP treatments had a significantly lower shear force than PFH treatment at 300 MPa ($p<0.05$), though the difference was not marked. Photographs of the sliced sample strips are shown in Fig. 3. The PFH and HFP treatments showed no changes in appearance relative to the control. Generally these samples were cut without any modifications in their structure regardless of the pressure level. However, sliced HUP treatment resulted in break down of the meat into its fiber structure, and the intensity of break down increased with increasing pressure levels. There have been many

Table 2. Effects of pressure levels and pressurization and heating procedures on the shear force of pork[1)]

Pressure (MPa)	Treatments[2)]		
	PFH	HFP	HUP
C[3)]	10.58±0.36^{Bx}	10.58±0.36^{Cx}	10.58±0.36^{Ax}
100	10.86±0.44^{Bxy}	12.10±0.79^{Bx}	9.38±2.27^{Ay}
200	13.12±1.50^{Ax}	13.58±0.87^{Ax}	6.44±0.83^{By}
300	12.10±0.58^{Ax}	9.70±0.54^{Cy}	4.34±0.54^{Cz}

[1)]Mean±SD from 24 replicate determinations.
[2)] PFH, pressurization followed by heating; HFP, heating followed by pressurization; HUP, heating under pressurization.
[3)] C, heated and non-pressurized control.
[A-C] Means with different superscripts within the same column are significantly different ($p<0.05$).
[x-z] Means with different superscripts within the same row are significantly different ($p<0.05$).

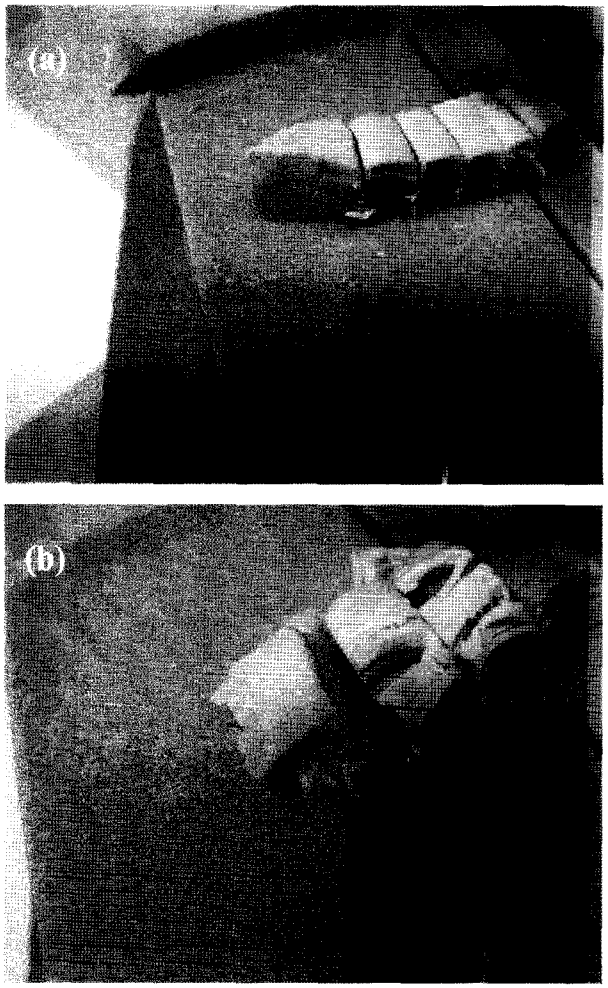

Fig. 3. Photographs of (a) control and (b) the sample heated under 300 MPa of pressure.

investigations examining the differences in meat texture from pressure-heat treatment relative to heat treatment alone (Bouton *et al.*, 1977a; Bouton *et al.*, 1977b; Macfarlane *et al.*, 1981; Locker and Wild, 1984). However, pressure-heat treated meat was also re-cooked for comparison to the cooked control, which was cold-shortened before cooking in these studies. In addition, little information about pressure followed by heating or *vice versa* is currently available.

In contrast to the lack of a tenderizing effect of pressure treatment below ambient temperature (Hong *et al.*, 2005), when meat was heated to 45-60°C under pressure, a marked improvement in tenderness was observed (Bouton *et al.*, 1977a; Macfarlane, 1985). Bouton *et al.* (1977a) proposed that the tenderizing effect of pressure-heat treatment was the pressure-induced dissociation of the native proteins, i.e. myofibrillar proteins present in an associated native form. Under pressure, these proteins are dissociated reversibly. When heat is applied under pressure, proteins denature irreversibly in the dissociated state, and denatured proteins cannot reform after pressure release, resulting in improved tenderness. However, cooked meat proteins form an associated and denatured state. If pressure is applied in this state, associated and denatured proteins cannot dissociate, thus, no effect on tenderness would be observed (Macfarlane, 1985). Consequently, these mechanisms could explain the results obtained in this study. Meanwhile, the decreased shear value at 300 MPa when compared to 200 MPa could be attributed to the role of connective tissue. It is generally accepted that pressure has no effect on connective tissue even if the temperature is elevated (Suzuki *et al.*, 1996). Bouton *et al.* (1978) also reported no changes in the properties of connective tissue when the beef was pressure-heat treated at 150 MPa and approximately 66°C. However, Ueno *et al.* (1999) observed a deformation of the structure in endomysium with increasing pressure up to 400 MPa. In the current study, the high heating temperature combined with 300 MPa of pressure might be enough to weaken the intramuscular connective tissue, which could potentially lead to the observed decrease in shear force with 300 MPa treatment.

Instrumental Color

Table 3 shows the effects of pressure-heat treatments on the CIE color of pork. The control had a significantly higher L-value, 65.7, when compared to raw meat ($p<0.05$). However, increasing the pressure level also significantly increased the L-value of pork ($p<0.05$). Among all other treatments, no significant differences in L-values were observed with the exception of 300 MPa HUP treatment ($p<0.05$). The a-values of PFH and HFP treatments decreased significantly at increased pressure levels ($p<0.05$). HUP treatment also tended to decrease the a-values of pork, however, this difference was not significant. With regard to b-values, all treatments had lower b-values than the control ($p<0.05$). The total color difference showed the same trend observed with

Table 3. Effects of pressure levels and pressurization and heating procedures on the CIE color of pork[1)]

Pressure (MPa)	Treatments[2)]		
	PFH	HFP	HUP
L-value			
C[3)]	65.68±0.42^{Cx}	65.68±0.42^{Dx}	65.68±0.42^{Bx}
100	66.70±0.92^{BCx}	67.20±0.88^{Cx}	66.15±0.50^{Bx}
200	67.53±1.41^{Bx}	68.55±1.07^{Bx}	68.43±0.48^{Ax}
300	70.53±0.81^{Ax}	70.40±0.78^{Ax}	68.13±0.31^{Ay}
a-value			
C	8.10±0.55^{Ax}	8.10±0.55^{Ax}	8.10±0.55^{Ax}
100	6.45±0.60^{By}	6.50±0.18^{By}	8.10±0.32^{Ax}
200	6.98±0.87^{By}	6.63±0.49^{By}	8.05±0.24^{Ax}
300	5.43±0.19^{Cy}	6.10±0.44^{Bx}	7.63±0.26^{Ax}
b-value			
C	15.65±0.53^{Ax}	15.65±0.53^{Ax}	15.65±0.53^{Ax}
100	15.48±0.88^{Ax}	15.60±0.37^{Ax}	13.33±0.17^{By}
200	14.18±1.24^{Bx}	14.88±0.61^{Bx}	13.48±1.34^{Bx}
300	13.40±0.24^{Bx}	13.98±0.30^{Cx}	12.68±0.51^{By}
Total color difference[4)]			
C	20.21±0.48^{Cx}	20.21±0.48^{Cx}	20.21±0.48^{Bx}
100	21.22±0.46^{BCx}	21.71±0.83^{Bx}	20.04±0.49^{By}
200	21.65±1.18^{Bx}	22.80±0.91^{Bx}	22.33±0.44^{Ax}
300	24.51±0.81^{Ax}	24.43±0.80^{Ax}	21.87±0.36^{Ay}

[1)]Mean±SD from six replicate determinations.
[2)] PFH, pressurization followed by heating; HFP, heating followed by pressurization; HUP, heating under pressurization.
[3)]C, heated and non-pressurized control.
[4)]Color of raw meat: L-value, 46.55; a-value, 9.2; b-value, 9.15.
[A-D] Means with different superscripts within the same column are significantly different ($p<0.05$).
[x-y] Means with different superscripts within the same row are significantly different ($p<0.05$).

L-values because the L-values were higher than the other color parameters. Although discoloration increased with increasing pressure levels, the discoloration might be more relevant to fresh meat (Hong *et al.*, 2003) because a lighter and less red color is typical of cooked meat. Therefore, the lighter appearance in cooked meat does not indicate deterioration and the high discoloration of pressurized pork did not limit the properties of cooked meat. Consequently, heating under pressurization could improve the meat quality in terms of moistness and tenderness without adversely affecting the appearance of the meat.

Acknowledgement

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References

1. Balny, C. and Masson, P. (1993) Effects of high pressure on proteins. *Food Rev. Int.* **9**, 611-628.
2. Boonyaratanakornkit, B. B., Park, D. S., and Clark, D. S. (2002) Pressure effects on intra- and intermolecular interactions within proteins. *Biochim. Biophys. Acta.* **1595**, 235-249.
3. Bouton, P. E., Ford, A. L., Harris, P. V., Macfarlane, J. J., and Óshea, J. M. (1977a) Pressure-heat treatment of postrigor muscle: Effects on tenderness. *J. Food Sci.* **42**, 132-135.
4. Bouton, P. E., Ford, A. L., Harris, P. V., Macfarlane, J. J., and Óshea, J. M. (1977b) Pressure-heat treatment of post-rigor muscle: objective-subjective measurements. *J. Food Sci.* **42**, 857-859, 865.
5. Bouton, P. E., Harris, P. V., Macfarlane, J. J., and Óshea, J. M. (1978) Pressure-heat treatment of meat: Effect on connective tissue. *J. Food Sci.* **43**, 301-303, 326.
6. Carballo, J., Cofrades, S., Fernández-Martín, F., and Jiménez-Colmenero, F. (2001) Pressure-assisted gelation of chemically modified poultry meat batters. *Food Chem.* **75**, 203-209.
7. Cheftel. J. C. (1995) Review: high pressure, microbial inactivation and food preservation. *Food Sci. Technol. Int.* **1**, 75-90.
8. Cheftel, J. C. and Culioli, J. (1997) Effects of high pressure on meat: A review. *Meat Sci.* **46**, 211-236.
9. Heremans, R. and Smeller, L. (1998) Protein structure and dynamics at high pressure. *Biochim. Biophys. Acta.* **1386**, 353–370.
10. Hong, G. P., Ko, S. H., Choi, M. J., and Min, S. G. (2007) Effects of pressure assisted freezing on physicochemical properties of pork. *Korean J. Food Sci. Ani. Resour.* **27**, 190-196.
11. Hong, G. P., Lee, S., and Min, S. G. (2003) Studies on physico-chemical properties of spreadable liver sausage during storage period. *Korean J. Food Sci. Ani. Resour.* **23**, 56-62.
12. Hong, G. P., Park, S. H., Kim, J. Y., Lee, S. K., and Min, S. G. (2005) Effects of time-dependent high pressure treatment on physico-chemical properties of pork. *Food Sci. Biotechnol.* **14**, 808-812.
13. Horgan, D. J. (1979) ATPase activities of sarcoplasmic reticulum isolated from rabbit and bovine muscle subjected to pre-rigor pressure treatment. *J. Food Sci.* **44**, 492-500.
14. Knorr, D., Heinz, V., and Buckow, R. (2006) High pressure application for food biopolymers. *Biochim. Biophys. Acta.* **1764**, 619-631.
15. Knorr, D., Schlueter, O., and Heinz, V. (1998) Impact of high hydrostatic pressure on phase transitions of foods. *Food Technol.* **52**, 42-45.
16. Ko, S. H., Hong, G. P., Park, S. H., Choi, M. J., and Min, S. G. (2006) Studies on physical properties of pork frozen by various high pressure freezing process. *Korean J. Food Sci. Ani. Resour.* **26**, 464-470.
17. Koohmaraie, M., Kennick, W. H., Elgasim, E. A., and Anglemier, A. F. (1984) Effect of prerigor pressurization on

the activity of calcium-activated factor. *J. Food Sci.* **49**, 680-684.
18. Locker, R. H. and Wild, D. J. C. (1984) Tenderisation of meat by pressure-heat involves weakening of the gap filaments in the myofibril. *Meat Sci.* **10**, 207-233.
19. Ma, H. J. and Ledward, D. A. (2004) High pressure/thermal treatment effects on the texture of beef muscle. *Meat Sci.* **68**, 347-355.
20. Macfarlane, J. J. (1973) Pre-rigor pressurization of muscle: effects on pH, shear value and taste panel assessment. *J. Food Sci.* **38**, 294-298.
21. Macfarlane, J. J. (1985) High pressure technology and meat quality. In: Developments in meat science. Lawrie, R. (ed), Elsevier, Inc., NY, Vol. 3, pp. 155-184.
22. Macfarlane, J. J., McKenzie, I. J., Turner, R. H., and Jones, P. N. (1981) Pressure treatment of meat: Effects on thermal transitions and shear values. *Meat Sci.* **5**, 307-317.
23. Priev, A., Almagor, A., Yedgar, S., and Gavish, B. (1996) Glycerol decreases the volume and compressibility of protein interior. *Biochemistry* **35**, 2061-2066.
24. Saad-Nehme, J., Silva, J. L., and Meyer-Fernandes, J. R. (2002) Osmolytes protect mitochondrial F_0F_1-ATPase complex against pressure inactivation. *Biochim. Biophys. Acta.* **1546**, 164-170.
25. Smeller, L. (2002) Pressure-temperature phase diagram of biomolecules. *Biochim. Biophys. Acta.* **1595**, 11-29.
26. Suzuki, A., Homma, Y., Kim, K., Ikeuchi, Y., Sugiyama, T., and Saito, M. (2001) Pressure-induced changes in the connectin/titin localization in the myofibrils revealed by immunoelectron microscopy. *Meat Sci.* **59**, 193-197.
27. Suzuki, A., Kim, K., and Ikeuchi, Y. (1996) Understanding the pressure effects on postmortem muscle. In: High pressure bioscience and biotechnology. Hayashi, R. and Balny, C. (eds), Elsevier, Inc., Japan, Vol. 13, pp. 289-298.
28. Suzuki, A., Watanabe, M., and Ikeuchi, Y. (1993) Effects of high-pressure treatment on the ultrastructure and thermal behaviour of beef intramuscular collagen. *Meat Sci.* **35**, 17-25.
29. Thawatchai, S. and Apichartsrangkoon, A. (2007) Combination effects of ultra-high pressure and temperature on the physical and thermal properties of ostrich meat sausage (yor). *Meat Sci.* **76**, 555-560.
30. Ueno, Y., Ikeuchi, Y., and Suzuki, A. (1999) Effects of high pressure treatments on intramuscular connective tissue. *Meat Sci.* **52**, 143-150.

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