Meat and Muscle Biology™

Short Communication: Combined Effects of Different Freezing and Thawing Rates on Meat Quality Characteristics of Aged Lamb Loins

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Abstract: The objective of this study was to determine the combined effects of different freezing and thawing rates on the quality characteristics of aged lamb loins. A total of 105 lamb loins at 1 d postmortem were vacuum-packaged and aged for 2 wk at −1.5°C. The loin samples were randomly assigned to 7 treatments, comprising 2 freezing (fast and slow) and 3 thawing rates (−1.5°C, 4°C, and 15°C), along with non-frozen (aged-only) control. Different freezing/thawing rates showed no influence on pH, shear force values, and color parameters of the aged lamb loins ($P > 0.05$). Fast freezing significantly decreased expressible moisture of the loins compared to slow freezing counterpart, regardless of thawing rates ($P < 0.05$). A significant interactive effect of freezing and thawing rates was found, where the slow freezing by fast thawing combination resulted in considerable increases in cooking loss. In contrast, fast freezing by fast thawing had a cook loss similar to never-frozen (aged only) control ($P > 0.05$). These findings suggest that fast freezing of previously aged meat will minimize the amount of moisture loss and thus improve quality attributes of the aged/frozen meat products, irrespective of thawing rates.

Keywords: lamb, aged meat, thawing, freezing, water-holding capacity
Meat and Muscle Biology 8(1): 18259, 1–7 (2024) **doi:10.22175/mmb.18259**
Submitted 8 July 2024 Accepted 8 November 2024

Introduction

Freezing is one of the most common industry practices used for long-term meat storage by hindering microbial growth. Despite its beneficial impacts on preservation, freezing can induce some quality defects of meat due to cryo-damage in muscles cells during the freezing and thawing process (Kiani and Sun, 2011). Freezing rates have direct impacts on determining the extent of cryo-damage in the muscle structure, where fast freezing results in even distribution of fine ice crystals both inside and outside the cells, thereby sustaining meat quality by minimizing tissue damage (Kim et al., 2024). Conversely, slow freezing tends to induce the formation of large ice crystals between muscle cells, inflicting more extensive damage to the muscle structure upon thawing (Kim et al., 2024). This results in increased thawing loss, diminished solubility of myofibrillar proteins, and reduced water-holding capacity (WHC) (Chabela and Oyague, 2004). Also, thawing conditions can influence meat quality (moisture loss in particular) by affecting membrane integrity and ultra-structures in muscle fibers (Giddings and Hill, 1978). Although extensive studies have investigated the independent effects of freezing and thawing on meat quality, there have been discrepant results between the studies. This discrepancy could be attributed to a potential interaction between freezing and thawing rates and their impacts on meat quality.

Postmortem aging is widely employed in the meat industry to enhance meat tenderness through the degradation of cytoskeletal myofibrillar proteins by endogenous proteolytic enzymes (Kim et al., 2012a). Recent studies have found that differences in meat quality attributes, including tenderness, color stability, and/or WHC between fresh chilled (never frozen) and frozen/thawed meat, could be narrowed if the meat were sufficiently aged prior to freezing (Farouk et al., 2009; Kim et al., 2013). However, to the best of our knowledge, there has been limited research investigating the interactive effect of freezing and thawing rates coupled with postmortem aging on the quality attributes of lamb loins. Therefore, the objective of this study was to determine the combined effects of different freezing/thawing rates on the quality attributes of pre-aged lamb loins.

Materials and Methods

Raw materials and sampling procedure

At 24 h postmortem, loins (*Longissimus thoracis lumborum*) from 105 lamb carcasses (4 mo old; average hot carcass weight 18 kg) were obtained at a commercial abattoir, vacuum packaged, placed on ice, and transported to the AgResearch Ruakura campus, New Zealand. After 2 wk of aging at −1.5°C, the vacuum-packaged loins were randomly assigned to 7 different treatments: combinations of 2 freezing (fast or slow) and 3 thawing (−1.5°C, 4°C, or 15°C) conditions and non-frozen control (aged-only for additional 6 wk; CON) treatment ($n = 15$). Detailed information for freezing conditions is provided in our previously published, similar study (Kim et al., 2015). In brief, for fast freezing, the vacuum-packaged loins were placed in a calcium chloride immersion tank (operating temperature at −17 to −18°C), where calcium chloride solution was circulated through the cooling system as the working fluid. Once the samples reached the target temperature (−18°C), the fast frozen loins were then stored in the air freezer at −18°C for 6 wk. The samples assigned to slow freezing were placed in the conventional air freezer (air velocity 1.3 m/s; operating temperature at −18°C) for 6 wk. Following storage, the frozen loins were allocated to 3 thawing-rate treatments, which were monitored using an Agilent HP 75000 Series C Data Acquisition & Control unit (Agilent Technologies Ltd, Englewood, CO, USA). The loins were taken out from their vacuum packs and cut into 4 sections for meat quality analyses.

pH

The pH of meat was measured using a calibrated handheld pH meter (Tesco 205, Testo AG, Lenzkirch, Germany). Duplicate readings by direct insertion to meat were taken for each loin sample after storage.

Expressible moisture

After each assigned storage times of the loins, an approximately 1.5 g (±0.3) of samples (triplicates) were weighed, wrapped with filter paper (Whatman #4), and centrifuged at 3,000 rpm for 15 min at 4°C. Expressible moisture contents as indication of drip loss were calculated as follows:

$$\text{Expressible moisture (\%)} = (\text{weight of expressed water in filter paper}/\text{weight of samples}) \times 100.$$

Cook loss

The 6-cm-thick loin cuts were cooked in a water bath set to 99°C until they reached an internal temperature of 75°C, monitored by a temperature logger (Eutech Instruments Pte. Ltd., Singapore). Following cooking, the samples were promptly transferred to an ice-water slurry to rapidly cool them down to a minimum of 4°C. Subsequently, the cuts were blotted dry and weighed. The weights before and after cooking and cooling were recorded, and percentage losses were calculated.

Shear force

Shear force was analyzed using a Tenderometer (Chrystall and Devine, 1991). After cooling of the cooked meat, 10 mm × 10 mm cross-section samples (10 replicates from each sample) were cut parallel to the fiber direction and sheared using the MIRINZ tenderometer (MIRINZ Inc., Hamilton, New Zealand) perpendicular to the fiber direction to determine peak shear force (kgF).

Color

After an hour of blooming, surface color of loins was measured using a Color Meter (CR-300; Konica Minolta Photo Imaging Inc., Mahwah, NJ, USA) calibrated using a standard white tile. CIE L^* (lightness), a^* (redness), and b^* (yellowness) values of loins were measured after each aging/freezing/thawing treatment. Three different locations for each meat sample were scanned and averaged for statistical analyses. The measured CIE values were used to calculate chroma $[(a^{*2} + b^{*2})^{1/2}]$ value (King et al., 2023).

Data analysis

The experimental design was a 2 x 3 factorial design, where 2 freezing rates and 3 thawing conditions along with non-frozen control were randomly applied to the lamb loins ($n = 15$). The data were analyzed using the REML directive of GenStat (12th Edition, 2010; GenStat for Windows, version 12.2.0.3717, VSN International, Oxford). Treatment effects were determined using Wald statistics. Least-squares means for all traits of interest were separated (F test, $P < 0.05$) by using least significant differences.

Results and Discussion

Temperature decline and pH

As presented in Figure 1, the loins assigned to fast freezing reached the target internal temperature of −18°C in less than 2 h. Specifically, it took about 20 min to pass through the critical zone (between −1°C and −8°C), where the majority of ice crystallization occurs in meat (Kiani and Sun, 2011). In contrast, the samples subjected to the slow freezing took approximately 7 h to reach −18°C and 140 min to pass through the critical zone. The time it takes for meat to pass through the critical temperature zone is a key factor in determining the size and characteristics of ice crystals. These ice crystals, in turn, influence the extent of cryo-damage to muscle tissue and ultimately affect the quality attributes of frozen and thawed meat (Kim et al., 2024). Distinct differences in thawing rates were observed between the 3 different thawing methods, as expected (Fig. 1). The loins placed in a 15°C water-bath took the shortest time to thaw to above 0°C, followed by those thawed at 4°C (less than 4 h). In contrast, the loins thawed at −1.5°C had the longest thawing period.

The various freezing/thawing treatments examined in this study did not yield any effect on the pH of the loins ($P > 0.05$; Table 1). This observation is in agreement with results from other studies, where no impact

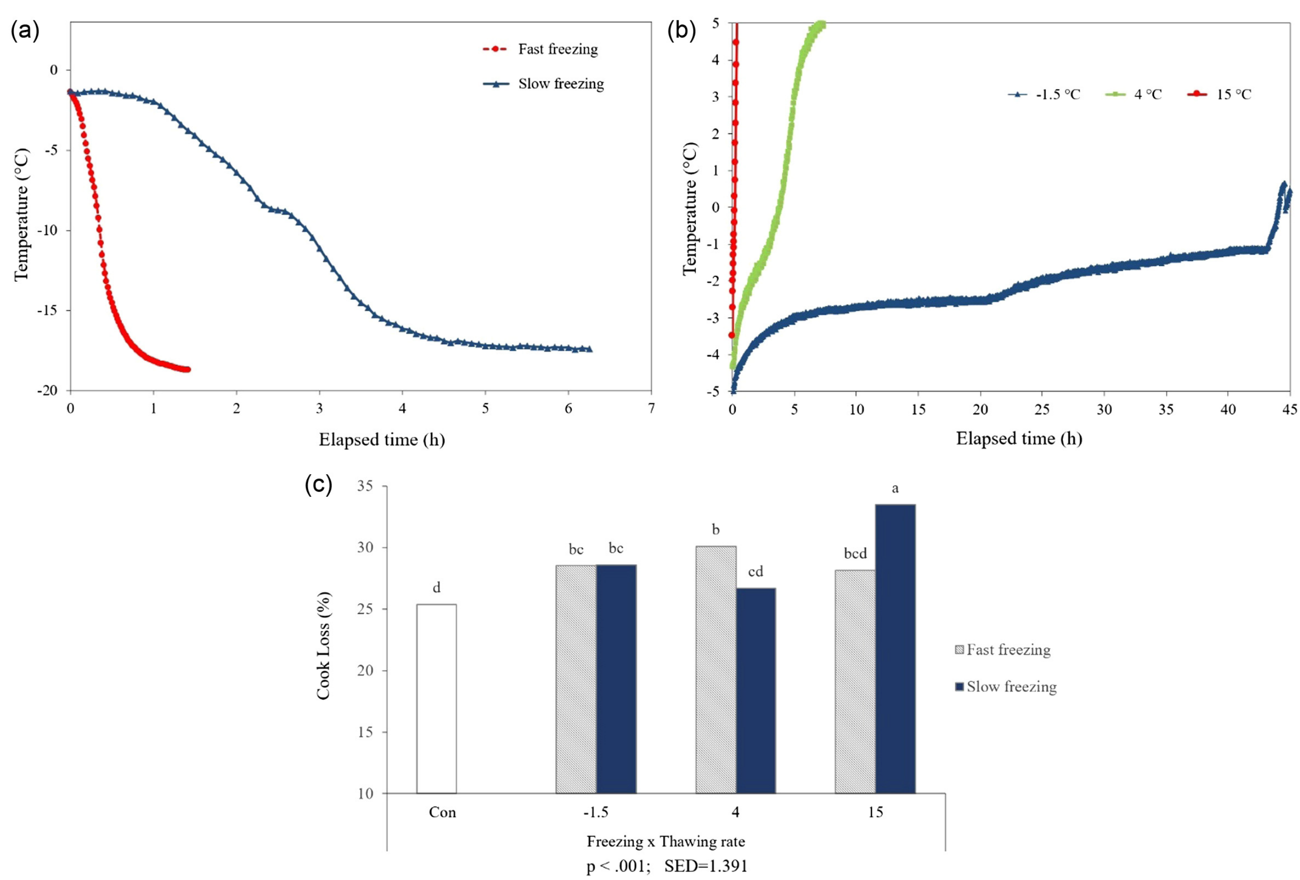

Figure 1. Trends in a) temperature decline using different freezing methods, b) temperature trends with different thawing methods, and c) cooking loss of aged lamb loins. [a–d]Least-squares means within a row lacking a common superscript letter indicate significant differences ($P < 0.05$). SED, standard error of difference.

Table 1. Effects of freezing and thawing methods and their interaction onmeat pH, shear force, water-holding capacity, and color attributes.

Traits	pH[A]	Shear force (kgF)[A]	Expressible moisture (%)	Color attributes L^*	a^*	b^*	Chroma
Control vs. freeze/thawing rate							
Aged-only control	5.84	3.82	1.83[b]	40.70	22.20[a]	9.04[a]	23.99[a]
Freeze/thawing	5.77	3.81	2.05[a]	39.29	20.68[b]	7.22[b]	21.93[b]
SED[B]	0.056	0.427	0.820	0.733	0.548	0.466	0.656
Freezing rate effect							
Aged-only control	5.84	3.82	1.83[b]	40.70	22.20	9.04	23.99
Fast	5.76	3.74	1.98[ab]	39.67	20.74	7.36	22.10
Slow	5.77	3.88	2.12[a]	38.90	20.63	7.08	21.76
SED	0.059	0.457	0.877	0.784	0.586	0.498	0.701
Thawing rate effect							
Aged-only control	5.84	3.82	1.83	40.70	22.20	9.04	23.99
−1.5	5.73	3.59	2.15	39.98	21.33	7.7	22.69
4	5.82	3.66	2.07	38.57	20.48	6.81	21.69
15	5.75	4.18	1.96	39.32	20.25	7.15	21.40
SED	0.063	0.485	0.930	0.832	0.621	0.528	0.744
P values							
Control vs. freeze/thawing	0.259	0.988	0.009	0.057	0.007	<0.001	0.002
Freezing rate	0.807	0.655	0.030	0.167	0.789	0.432	0.499
Thawing rate	0.180	0.279	0.117	0.119	0.086	0.12	0.090
Freezing * thawing	0.954	0.673	0.355	0.364	0.537	0.133	0.501

[A]pH and shear force were measured after 8 weeks of storage.

[B]Standard error of difference.

[a,b]Least-squares means within a row lacking a common superscript letterindicate significant differences ($P < 0.05$).

Control; never frozen, fresh lamb loin.

of freezing/thawing rates on pH of meat was found (Kim et al., 2023).

Expressible moisture and cook loss

There was a significant freezing rate effect (Table 1), where fast freezing resulted in similar expressible moisture compared to the aged-only (never frozen) control group ($P > 0.05$). In contrast, the loins assigned to slow freezing had a higher expressible moisture than the control ($P < 0.05$). This outcome can be attributed to the formation of small, fine ice crystals during fast freezing, which resulted in minimal water translocation within the intracellular space of the meat (Aberle et al., 2001). Consequently, loins subjected to fast freezing exhibited lower expressible moisture after thawing compared to those subjected to slow freezing. No significant impacts of thawing methods or the interaction between freezing and thawing on expressible moisture were found (Table 1).

For cook loss, a significant interaction between freezing and thawing rates was found (Fig. 1C). While the aged-only (never frozen) control had the lowest cook loss among treatments, the loins subjected to the slow freezing by fast thawing combination had the highest cook loss among treatments ($P < 0.05$). In contrast, the loins assigned to fast freezing followed by fast thawing had a similar cook loss to the aged-only (never frozen) control ($P > 0.05$), indicating that the initial freezing rate has a more significant impact on moisture loss during cooking than the thawing rate. Furthermore, the loins subjected to fast freezing showed similar cook loss across frozen/thawed treatments, regardless of thawing conditions ($P > 0.05$). This supports the overriding impacts of fast freezing on cook loss compared to thawing rates.

While extensive studies have been conducted to determine the effects of freezing or thawing on meat quality, particularly WHC, conflicting results have been reported. For example, postive effects of rapid thawing (reduced thawing times) on WHC have been noted (Gonzalez-Sanguinetti et al., 1985; Leygonie et al., 2012), suggesting fast thawing results in less moisture loss. Conversely, adverse influeces of rapid thawing have been also reported, where an increased thawing rate resulted in higher cook loss (Ngapo et al., 1999; Yu et al., 2010). These discrepancies could be related to overlooking the potential combined impacts of both initial freezing rate and subsequent thawing conditions. The present study clearly demonstrated the interactive impacts between freezing and thawing rates on cook loss. The results emphasized the predominant influence of the initial freezing rate, indicating that thawing rates are less critical when the loins are fast frozen. However, if the meat is slow frozen, then fast thawing should be avoided to minimize moisture loss.

It has been well-established that fast freezing results in finer and uniformly distributed ice crystals both inside and outside muscle cells, causing minimal cryo-damage (Kiani and Sun, 2011). Thus, when subjected to thawing (irrespective thawing rates), the ice crystals have only a limited effect on muscle ultra-structure. In contrast, slow freezing leads to larger and more extracellular ice crystal formations, resulting in much more severe cryo-damage to muscles upon thawing. Consequently, fast thawing after slow freezing may exacerbate cryo-induced damage in muscle fibers, resulting in considerable moisture loss during cooking. Furthermore, since cook loss involves water expelled from the myofibrillar matrix during cooking, while drip loss primarily comprises extramyofibrillar water (Straadt et al., 2007), it is reasonable to postulate that combined effects of freezing and thawing rates can result in different extents of water mobility and subsequent migration of myowater within myofibril structures. This postulation warrants further research for confirmation.

Shear force

As displayed in Table 1, different freezing/thawing rates did not affect the shear force values of the lamb loins ($P > 0.05$). The shear force values were around 4 kgF, which is considered very tender (Vieira et al., 2009), likely due to aging coupled with freezing. The mechanism responsible for tenderization of aged meat involves changes in integrity of the structural proteins such as desmin, titin, troponin-T, and others (Huff-Lonergan et al., 1996). Many studies have reported that the (instrumental) tenderness of the aged/frozen loins demonstrated comparable values to the non-frozen control, regardless of the diverse freezing and thawing techniques employed (Wiklund et al., 2009; Kim et al., 2011; Kim et al., 2012b), confirming the beneficial impact of aging prior to freezing on meat tenderness.

Color

In general, there were no distinct freezing/thawing rate impacts on initial color attributes of the lamb loins (Table 1). No significant treatment impacts on the L^* values (lightness) of the lamb loins were found (Table 1). However, there was a trend ($P = 0.057$) indicating that the frozen/thawed loins appeared slightly darker than the non-frozen control, which is consistent with a previous study conducted by Kim et al. (2011). The aged-only (non-frozen) control had slightly higher a^* (redness), b^* (yellowness), and chroma (color intensity) values compared to the loins subjected to freezing/thawing ($P < 0.05$). It is well-established that freezing/thawing deteriorates the surface meat color, making it darker and dull-red compared to never-frozen fresh meat, likely due to inferior blooming ability. Upon thawing and exposing meat to air, myoglobin can bind oxygen in the oxygenation process to form oxymyoglobin, the pigment responsible for bright red color. However, respiratory enzymes in mitochondria can also regain their oxygen-utilizing activities, leaving less oxygen available for myoglobin oxygenation, resulting in darker and/or dull-red appearance of meat (Suman and Nair, 2017). In the present study, however, although significant, the differences in color attributes between frozen/thawed meat and aged-only (never frozen) control are less than 2 units, which would be practically less meaningful. This could be attributed to the fact that in this study, the frozen/thawed samples were aged prior to freezing, which likely assisted blooming ability by suppressing oxygen-utilizing enzyme activities during aging (Kim et al., 2011).

Conclusion

The results of the current study confirmed the importance of fast freezing on WHC of frozen/thawed meat. Slow freezing resulted in increased expressible moisture of lamb loins, whereas fast frozen loins had a similar expressible moisture compared to never-frozen (aged only) control, regardless of thawing rates. Importantly, the study found a significant interactive impact of freezing and thawing rates on cook loss, where slow freezing followed by fast thawing resulted in considerable moisture loss during cooking. Conversely, fast freezing followed by fast thawing resulted in a cook loss similar to the never frozen (aged-only) control, suggesting that the initial freezing rate has a more significant impact on moisture loss during cooking compared to thawing rate. The study also found that thawing rates are less critical when the loins are fast frozen. No significant impacts of freezing and thawing rates on shear force values and color attributes of aged lamb loins were found. These observations suggest that fast freezing of previously aged meat will minimize the amount of water loss due to the freezing/thawing process and thus add more value to the aged/frozen meat products by lowering moisture loss and preserving soluble nutrients. Additionally, the use of fast thawing, particularly for the slow frozen lamb meat, is not recommended, as it can cause significantly higher cooking loss compared to other freezing/thawing combinations.

Acknowledgments

This work was funded by the AgResearch Capability Fund. The authors would like to acknowledge Kevin Taukiri and Pete Dobbie (Food Assurance and Meat Quality team at AgResearch) for assistance in sample and data collection and Dr. John Waller for statistical analysis.

Conflict of Interest: The authors declare there are no conflicts of interest.

Author Contributions: Y.H.B. Kim: Conceptualization, Investigation, Supervision, Writing–Original draft preparation and Editing, Funding acquisition; R. Kemp: Data curation, Methodology; D.J. Shin: Writing–Reviewing and Editing, Data analysis; A. Stuart: Data curation, Methodology.

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