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Fresh and Frozen Storage on Meat Quality and Sensory Attributes of Lamb Loins and Legs

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Abstract: The objective of this study was to evaluate fresh and frozen storage of lamb *longissimus lumborum* (LL) and *semimembranosus* (SM). Wether lambs ($n = 12$) were raised and harvested at North Dakota State University. After a 24-h chill, loins and legs were split in half and randomly assigned to fresh (FRSH) or frozen (FRZN) treatments. FRSH halves were stored at 3°C for 14 d while FRZN halves were stored at −18°C for 13 d + 1 d to thaw at 3°C. Samples were collected to evaluate sensory attributes, Warner-Bratzler shear force, cook loss, drip loss, troponin-T (TnT) degradation, and lipid oxidation. Data were analyzed using PROC MIXED of SAS Studio®. Experimental units were loin or leg with means being separated with the PDIFF option and were considered significant when $P < 0.05$. In FRSH-LL, sensory samples scored higher in overall like, tenderness, and juiciness ($P \leq 0.03$) compared with FRZN-LL samples. No differences in overall like, flavor, tenderness, or juiciness scores ($P \geq 0.77$) were observed between FRSH-SM and FRZN-SM. FRSH-LL and FRSH-SM had less drip loss compared with FRZN-LL and FRZN-SM ($P < 0.0001$, $P = 0.0003$, respectively). FRSH lamb LL and SM had greater degradation of TnT ($P \leq 0.0008$) compared with FRZN lamb. Malondialdehyde levels were not different ($P > 0.05$) between treatments within each muscle. However, no other meat quality differences were observed ($P \geq 0.10$). Our results demonstrate that lamb legs may be frozen for 13 d without negative effects on palatability whereas lamb loins should be kept fresh to offer the greatest opportunity for consumer satisfaction.

Key words: lamb, meat quality, frozen storage, protein degradation, lipid oxidation, sensory attributes
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Introduction

A common challenge in the US lamb industry is inconsistencies in the supply of fresh lamb related to lambing time and rates in the traditional US lamb system, with about 80% of the US lamb crop being born in the first 5 mo of the year (Redden et al., 2018). Use of frozen lamb could resolve some of these issues during spikes in lamb demand around religious holidays, such as Easter and Passover (USDA-ERS, 2012). However, consumers heavily discriminate against frozen meat in the retail space (Bueno et al., 2013; Lambooij et al., 2019) due to perceived issues with product quality.

There is general acceptance among research that the freezing process of meat products leads to a degradation of ultrastructure due to formation of ice crystals during the freezing process. Visible changes to the ultrastructure include cosmetic changes in color and texture, with frozen lamb appearing darker and more yellow with less mushy texture than fresh lamb (Stenberg et al., 2022). Additionally, the degradation of the ultrastructure may lead to palatability issues due to loss of water during the thawing process (Devine and Graafhuis, 1995; Ballin and Lametsch, 2008).

Furthermore, research suggests that meat products continue to deteriorate due to chemical reactions, such as lipid oxidation, even in frozen products (Zhang et al., 2005). In an effort to combat these challenges, significant advances have been made in the meat-processing and packaging industries, with vacuum and modified-atmosphere packaging working in

combination with freezing to improve product quality during a time of increasing demand for shelf-ready meat products (Muela et al., 2015). While a significant amount of research is being conducted to determine how different freezing techniques can impact the bacterial community and shelf life of meat (Liang et al., 2021), impacts on sensory attributes in technologies like super-chilling and subfreezing remain relatively unexplored.

Research on meat quality and sensory attributes of frozen lamb presents widely varied conclusions on whether frozen lamb is a viable option for US retailers (Smith et al., 1968; Kim et al., 2013; Muela et al., 2016). In a comparison of lamb from twin-born paired rams, Stenberg et al. (2022) concluded that frozen racks and loins were darker in color, with increased drip loss and less desirable tenderness and flavor characteristics after the freeze-thaw process.

There is anecdotal evidence for fresh preferences amongst US retailers and consumers. Li et al. (2022) confirmed that Chinese consumers had a 66.7% preference of fresh over frozen lamb during at-home cooking use. Conversely, Ufer et al. (2020) evaluated imported lamb characteristics and preferences to determine the trend toward chilled (fresh) lamb from Australia yet frozen New Zealand lamb products.

The lamb processing industry is less organized and researched compared with other red meat processing industries in the US; therefore, there are limited data for benchmarking lamb quality. It is important that research is conducted to understand exactly how the freezing process affects meat quality and sensory attributes of American lamb in a frozen state to provide better research-based guidance to processors, retailers, and foodservice on the consumer perceptions of frozen lamb and whether frozen lamb is acceptable for US consumers.

Our objectives for this research were to evaluate sensory attributes, meat quality, protein degradation, and lipid oxidation between fresh and frozen lamb using the *longissimus lumborum* (LL) and *semimembranosus* (SM) muscles and provide recommendations to US processors on practical options for storage of lamb.

Materials and Methods

Experimental design

North Dakota State University (NDSU) raised Dorset wether lambs ($n = 12$), 6 to 7 mo of age, were slaughtered at the NDSU Meats Laboratory using typical slaughter and dressing procedures under USDA-FSIS inspection. September/October born lambs were fed a complete ration post-weaning and harvested at a predicted USDA Yield Grade 3. The moderate framed Dorset genetics resulted in fatter lambs than preferred, yet similar to commercial US production. After a 24-h chill at 1°C, carcass traits used for USDA yield grading and quality grading determination were performed by trained NDSU personnel.

After grading, loin (IMPS 232) and leg (IMPS 233B) subprimals were collected from each carcass. Subprimals were split in half along the backbone, and each side was randomly assigned to either fresh (FRSH) or frozen (FRZN) treatments. Prior to treatment application, loin halves were trimmed to ∼0.6 cm fat depth. Each half was weighed before being vacuum sealed. Subprimal halves assigned to the FRSH treatment were stored in a cooler at 3°C for 14 d before fabrication while subprimal halves assigned to the FRZN treatment were stored in a freezer at −18°C for 13 d + 1 d of thawing at 3°C before fabrication. FRZN samples were frozen at ∼30 h postmortem.

Sample preparation

Before fabrication, subprimal halves were removed from vacuum bags and reweighed, and weight loss was calculated. Sample collection of LL began at the cranial end of the loin subprimal halves with the following samples removed in sequential order: ∼1.27-cm bone-in chop for protein degradation and lipid oxidation analysis, a ∼1.27-cm chop bone-in for drip loss analysis, a ∼2.54-cm bone-in chop for Warner-Bratzler shear force (WBSF) and cook loss analysis, and four to five 2.45-cm bone-in chops for sensory analysis. The SM was removed from the leg subprimal halves with sample collection beginning at the distal end of the muscle, and chops were removed in the same manner as the LL. Samples for protein degradation and lipid oxidation were frozen at −80°C until analysis. Samples for WBSF and cook loss analyses and sensory evaluation were vacuum-sealed and stored at 3°C until analysis. Sensory evaluation occurred ∼12 h post fabrication, with WBSF and cook loss analysis occurring ∼24 h post fabrication.

Meat quality analyses

Drip loss analysis was conducted immediately after chop collection and assignment. An ∼25-g rectangular subsample was cut from each LL and SM chop, beginning weight recorded, and then the subsample was suspended from a large paperclip in a wire closure

bag to collect water drip for 24 h at 3°C. After 24 h, samples were removed from the bags, lightly blotted dry with lint-free paper towels, and reweighed to determine ending weight. Drip loss was determined using the following equation:

$$\left[1 - \frac{(beginning\ weight\ -\ ending\ weight)}{beginning\ weight}\right].$$

Chops for WBSF and cook loss analysis were allowed to equilibrate to room temperature (~20°C) prior to cooking. Raw weight of the chops was recorded before inserting a flexible wire thermocouple (Omega Engineering Inc., Norwalk, CT) into the geometric center of the chop. Chops were cooked on clamshell style grills (George Foreman Model No. GRP99, Columbia, MO) preheated to 176°C to an internal temperature of 71°C. Chops were allowed to cool to room temperature before a cooked weight was taken. Cook loss was determined using the following equation:

$$\left[1 - \frac{(raw\ weight\ -\ cooked\ weight)}{raw\ weight}\right].$$

Three, 1.27-cm cores were removed from the center of each chop parallel to the muscle fibers (AMSA, 2016). Cores were sheared perpendicular to the muscle fibers using a shear force machine (GR-151, Tallgrass Solutions, Manhattan, KS) with shear force being recorded in kilograms of force. The average of 3 cores was used for statistical analysis.

Sensory analysis

Sensory analysis was conducted in accordance to the AMSA Guideline (2016). The NDSU Institutional Review Board (IRB #3570) approved all research components utilizing human subjects in sensory evaluation. Consumer panelists were recruited via email lists of the NDSU campus faculty and staff. The untrained consumer panelists ($n = 84$) were served five, 1.27-cm cubed samples in a classroom with standard lighting, with 6 panels consisting of 12 to 15 panelists. All panels were conducted on the same day. *Longissimus lumborum* and SM chops were cooked in the same manner as described for WBSF with the endpoint temperature being 71°C. All samples were kept warm and presented in 2-oz covered plastic cups which were labeled with a three-digit code. Samples were presented to panelists in a predetermined randomized order. The first sample presented was a warm-up sample which was not used in analysis. The warm-up sample used was a portion of the *longissimus thoracis* from the same experimental animals. The subsequent samples were SM and LL samples, which were distributed to panelists in a randomized order. Panelists were instructed to take two bites of each sample before recording their scores. Panelists were provided with unsalted crackers and distilled water to cleanse their palates between samples. Panelists were asked to evaluate each sample for overall like, flavor like, tenderness like, and juiciness like on a 0 to 100 continuous line scale, with 0 being greatest imaginable dislike and 100 being greatest imaginable like.

Lipid oxidation analysis

From frozen samples, approximate 1-g samples were minced by knife on a precooled cutting board, and weights were taken and recorded to 4 decimal places. Samples were homogenized in 4 mL of extraction buffer (10 m*M* sodium phosphate, pH 7.2; 2% [wt/vol] sodium dodecyl sulfate [SDS]) with added 40 µL of 5% (wt/vol) butylated hydroxytoluene in methanol using a Polytron Kinematica (10/35 with controller and PTA 10S generator; Brinkmann, Westbury, NY) on wet ice. The homogenate was centrifuged at $15{,}000 \times g$ and 10°C for 15 min (Allegra 25R Centrifuge with TA-14-50 fixed angle rotor, Beckman Coulter, Fullerton, CA). The clear supernatant was then transferred to 1.5-mL microtubes and stored at −80°C until analysis lipid oxidation.

Lipid oxidation was assessed using the OxiSelect thiobarbituric acid reactive substances (TBARS) assay kit (malondialdehyde [MDA] quantification) (Cell Biolabs Inc., San Diego, CA) following manufacturer procedures with modifications as follows: samples were incubated in dry heating blocks at 95°C for 45 min, cooled, and centrifuged at $10{,}000 \times g$ and 12°C for 12 min. Results are expressed as mg MDA/kg of meat.

Troponin-T degradation by Western blotting analysis

Protein extraction. Protein was extracted using modifications of Huff-Lonergan et al. (1996). Partially thawed frozen ~1-g samples were minced by knife on a pre-cooled cutting board and homogenized in 10 mL of extraction buffer (10 m*M* sodium phosphate, pH 7.2; 2% [wt/vol] SDS, pH 7.2) using a Polytron Kinematica (10/35 with controller and PTA 10S generator; Brinkmann) on wet ice. The homogenate was centrifuged at $3{,}000 \times g$ and 10°C for 20 min (Allegra 25R Centrifuge with TA-5.1-500 swinging bucket rotor, Beckman Coulter). The clear supernatant was transferred to 1.5-mL microtubes and stored at −80°C until

further analysis. The protein concentration of each extract was determined using the Pierce Detergent Compatible Bradford Assay with bovine serum albumin as the standard (Thermo-Fisher 23246; Rockford, IL) and in a microplate format.

Protein separation by SDS-PAGE and semi-dry transfer to membranes. Protein gel samples were prepared by setting all protein extract concentrations to 0.3 µg/µL in a sample gel buffer/tracking dye solution (Wang, 1982) (3 m*M* ethylenediamine tetraacetic acid [EDTA]; 3% [wt/vol] SDS; 30% [vol/vol] glycerol; 0.003% [wt/vol] pyronine Y; 9.4 m*M* Tris, pH 8.0; with 6.25% [vol/vol] 2-mercaptoethanol), heated at 65°C for 15 min, and then frozen at −80°C until protein separation by electrophoresis.

Protein gel samples were thawed, and 9 µg protein/lane was loaded onto 1.5-mm thick 15% polyacrylamide separating gels (0.38 *M* Tris, pH 8.8; 0.1% [wt/vol] SDS; 0.05% [wt/vol] ammonium persulfate [AMPER]; 0.05% [vol/vol] TEMED) with 5% polyacrylamide stacking gel (0.125 *M* Tris, pH 6.8; 0.1% [wt/vol] SDS; 0.075% [wt/vol] AMPER; 0.125% [vol/vol] TEMED) both with 37.5:1 acrylamide:bis crosslinking and run at a constant voltage of 120 V for 2 h 15 min in a running buffer (25 m*M* Tris; 0.192 *M* glycine; 2.0 m*M* EDTA; 0.1% [wt/vol] SDS) (Melody et al., 2004) on a BioRad Mini-PROTEAN Tetra Cell system (BioRad Laboratories, Hercules, CA). A pooled control consisting of equal amounts of LL and SM sample extract was run in lanes 2 and 10 of every gel for normalization of data.

Proteins were transferred onto 0.45-µ polyvinylidene difluoride (PVDF) membranes (Trans-Blot Turbo RTA Transfer Kit, LF PVDF; BioRad Laboratories, Hercules, CA) using the Trans-Blot Turbo Transfer System and reagents (BioRad Laboratories) at a limited voltage of 25 V and constant 2.5 A for 12 min.

Immunoblotting. Membranes were blocked in phosphate buffered saline (PBS)-Tween (100 m*M* sodium phosphate, pH 7.4; 100 m*M* sodium chloride; 0.1% [vol/vol] Tween-20) with 5% (wt/vol) nonfat dry milk for 1 h at room temperature, incubated overnight at 4°C in mouse monoclonal anti-rabbit troponin-T (TnT) antibody (Clone JLT-12, Sigma-Aldrich Chemical, St. Louis, MO), diluted at 1:35,000 in PBS-Tween, washed, and incubated for 1 h at room temperature with goat anti-mouse antibody conjugated with horseradish peroxidase (A28177) (ThermoFisher Scientific, Waltham, MA) diluted at 1:75,000 in PBS-Tween. Troponin-T immunoreactivity was detected by chemiluminescence (ECL Prime Western Blotting Detection Reagent Kit, GE Healthcare, Chicago, IL) using the FluorChem FC2 imaging system (Protein Simple). Densitometry measurements were performed using the AlphaEaseFC software (Alpha Innotech Corporation) with 1D Multi using 50% of the total lane width and a horizontal base with peak detection being adjusted manually. The ratio of the intensity of the sample bands to the intensity of the 30-kDa band in the pooled control was used to analyze the differences in treatments. All samples were run in duplicate.

Statistical analysis

Data were analyzed in a complete randomized design using the PROC MIXED procedure of SAS Studio® (SAS Institute, Cary, NC). Analysis of variance for data for meat quality, sensory attributes, TnT Western blot data, and lipid oxidation was completed with the fixed effect as treatment. Least-squares means were separated with the PDIFF option. Means were considered significant when $P \leq 0.05$.

Results and Discussion

Carcass quality

Lamb carcasses were relatively homogenous across all carcass quality parameters. Lambs were harvested with an average of 61.2 kg live weight. The average hot carcass weight was 34.5 kg with a range of 33 to 37 kg. The average dressing percentage was 56.6% with a range of 55.5% to 57.9%. The average USDA yield grade (YG) was a 5.0 with a range of 3.4 to 5.9. Final USDA YG designation was either YG 3 ($n = 1$), YG 4 ($n = 5$), or YG 5 ($n = 6$).

All carcasses were graded USDA High Choice ($n = 4$) or Low Prime ($n = 8$).

Meat quality

Differences were not observed between treatments for subprimal weight loss, cook loss, or WBSF in either the LL or SM ($P > 0.05$; Table 1). However, FRSH-LL and FRSH-SM had less drip loss compared with that of FRZN-LL and FRZN-SM ($P < 0.0001$, $P = 0.0003$, respectively). These results are consistent with other studies (Kim et al., 2011, 2013; Choe et al., 2016) which indicate that freezing early in the aging process of meat increases drip loss after thawing. Additionally, Bueno et al. (2013) found that frozen storage did not influence lamb meat quality characteristics other than a deleterious effect on water-holding capacity, concurring with the results in the present study. Research on Spanish-raised lamb showed little difference in meat

Table 1. Least-squares means of the effect of fresh and frozen storage[1] of American lamb[2] on subprimal weight loss, drip loss, cook loss, and Warner Bratzler shear force (WBSF) values on *longissimus lumborum* and *semimembranosus* chops

	Fresh	Frozen	SEM	*P* Value
Longissimus lumborum				
Subprimal weight loss, %	0.87	1.61	0.44	0.12
Drip loss, %	0.85[a]	4.80[b]	0.45	<0.0001
Cook loss, %	17.48	17.55	1.43	0.96
WBSF, kg	2.88	3.21	0.30	0.30
Semimembranosus				
Subprimal weight loss, %	0.28	0.58	0.16	0.10
Drip loss, %	2.30[a]	6.67[b]	0.77	0.0003
Cook loss, %	19.13	21.18	1.87	0.30
WBSF, kg	3.19	3.40	0.28	0.49

[1]Vacuum packaged fresh samples ($n = 12$) were stored for 14 d at 3°C while frozen samples were stored for 13 d at −18°C.

[2]Dorset wether lambs, 6 to 7 mo of age, sourced from North Dakota State University sheep unit.

[a,b]Means within the same row without common superscripts differ ($P < 0.05$).

quality and consumer acceptability of fresh versus frozen lamb (Muela et al., 2010, 2012). However, it should be mentioned that both studies stored frozen lamb up to a maximum of 6 mo; therefore, it may be crucial for further research to be conducted to gain a better understanding of how long lamb may remain in frozen storage before quality deterioration becomes an issue with consumer acceptance.

Sensory attributes

Demographics for survey participants are shown in Table 2. Sensory results are summarized in Table 3. FRSH-LL had higher overall like ($P = 0.01$), tenderness ($P = 0.01$), and juiciness ($P = 0.03$) scores compared with FRZN-LL. These sensory attributes indicated that consumers had higher acceptance of FRSH-LL for tenderness and juiciness, which could be attributed to increased protein degradation in FRSH due to aging that occurred at lower temperature that was curtailed at freezer temperatures. Flavor scores did not differ between FRSH-LL and FRZN-LL. These results are slightly different from other research that suggests that consumers did not have a preference for fresh versus frozen lamb loin, although increased water loss was observed (Muela et al., 2010, 2012). Not all panelists in our sensory panels self-identified as frequent lamb eaters. Therefore, some of the difference in flavor perceptions of lamb meat may be

Table 2. Demographic characteristics of consumers ($n = 84$) who participated in sensory panels of fresh and frozen[1] American lamb[2] *longissimus lumborum* and *semimembranosus* chops

	Count	Frequency (%)
Gender		
Male	31	40
Female	53	60
Age		
Under 20	20	24
20 to 29	56	67
30 to 39	3	4
40 to 49	4	5
50 to 59	1	1
Working Status		
Student	45	54
Part-time	26	31
Full-time	13	15
Ethnicity		
Caucasian	69	82
Hispanic	5	6
Asian	9	11
Other	1	1
Previous Lamb Consumer		
Yes	63	75
No	21	25

[1]Vacuum packaged fresh samples ($n = 12$) were stored for 14 d at 3°C while frozen samples were stored for 13 d at −18°C.

[2]Dorset wether lambs, 6 to 7 mo of age, sourced from North Dakota State University sheep unit.

Table 3. Least-squares means of the effect of fresh and frozen storage[1] of American lamb[2] on consumer sensory attribute scores on a 0–100 continuous scale[3] of *longissimus lumborum* and *semimembranosus* chops

	Fresh	Frozen	SEM	*P* Value
Longissimus lumborum				
Overall Like	64[a]	56[b]	3	0.01
Flavor Like	64	59	3	0.14
Tenderness Like	62[a]	55[b]	3	0.01
Juiciness Like	59[a]	52[b]	3	0.03
Semimembranosus				
Overall Like	58	57	4	0.85
Flavor Like	60	60	3	0.92
Tenderness Like	54	54	4	0.99
Juiciness Like	52	53	4	0.77

[1]Vacuum packaged fresh samples ($n = 12$) were stored for 14 d at 3°C while frozen samples were stored for 13 d at −18°C.

[2]Dorset wether lambs, 6 to 7 mo of age, sourced from North Dakota State University sheep unit.

[3]0 = greatest imaginable disliking, 100 = greatest imaginable liking.

[a,b]Means within the same row without common superscripts differ ($P < 0.05$).

between frequent and infrequent consumers of lamb (Watkins et al., 2013).

There were no differences in overall like or flavor, tenderness, or juiciness likes between FRSH-SM and FRZN-SM ($P > 0.05$). While we saw differences in proteolysis and drip loss in the SM, these differences did not influence consumer panel preferences. These sensory results could be explained by the background toughness inherently in the SM due to muscle use in the live animal as observed by Tschirhart-Hoelscher et al. (2006) and possible presence of increased connective tissue (Dubost et al., 2013). It is likely that we would not see significant differences in consumer perceptions of meat palatability characteristics due to all SM samples being viewed as a "tough" cut in relation to other lamb retail cut options.

Protein degradation

A representative Western blot is shown in Figure 1 with the immunoreactive bands of interest labeled with molecular weights. Results for TnT are summarized in Figure 2. Treatment did not influence ($P > 0.05$) 42-kDa TnT in the LL. FRZN-LL had greater 37- to 39-kDa ($P = 0.0002$), 35-kDa ($P < 0.0001$), and 34-kDa ($P < 0.0001$) TnT immunoreactive bands compared with those of FRSH-LL. Conversely, FRSH-LL had greater 32-kDa ($P < 0.0001$) and 30-kDa ($P < 0.0001$) TnT immunoreactive bands compared with those of FRZN-LL. FRZN-SM had greater 42-kDa ($P = 0.02$), 37- to 39-kDa ($P < 0.0001$), 35-kDa ($P < 0.0001$), and 34-kDa ($P = 0.01$) TnT immunoreactive bands compared with FRSH-LL. Conversely, FRSH-SM had greater 32-kDa ($P = 0.0008$) and 30-kDa ($P < 0.0001$) TnT immunoreactive bands compared with FRZN-SM. Therefore, it can be concluded FRSH-LL and FRSH-SM had more degradation of TnT compared with that of FRZN-LL and FRZN-SM as shown by the increase in the 30-kDa immunoreactive band (MacBride and Parrish, 1977). These results were expected similar to Olson et al. (1976) as the study design did not allow for FRZN samples to age for longer than 30 h postmortem.

However, these protein degradation findings do offer further explanation of other observed results in the present study. Previously, increased water-holding capacity of aged meat was thought to be explained by the meat having less water to lose during the aging process due to moisture loss in the early postmortem period (Joo et al., 1999). However, this hypothesis is challenged by observations of Farouk et al. (2007, 2009) who found that there were no significant changes in moisture content in the early postmortem period and during aging and who observed that water-holding capacity increases with longer aging periods. Farouk et al. (2012) proposed the sponge effect where they hypothesized that, during the conversion of muscle to meat, channels may be formed due to the decrease in pH and muscle contraction due to rigor, and these channels may allow for water to more easily be lost. However, as postmortem aging occurs, the structure of these channels may be disrupted due to proteolysis of structural proteins. The breakdown of structural proteins is pivotal to the increased water-holding capacity of aged meat due to the ability of water to be physically trapped in the meat. Furthermore, there is the potential that the increased viscosity of water in meat (due to soluble protein) may further reduce the ability of water

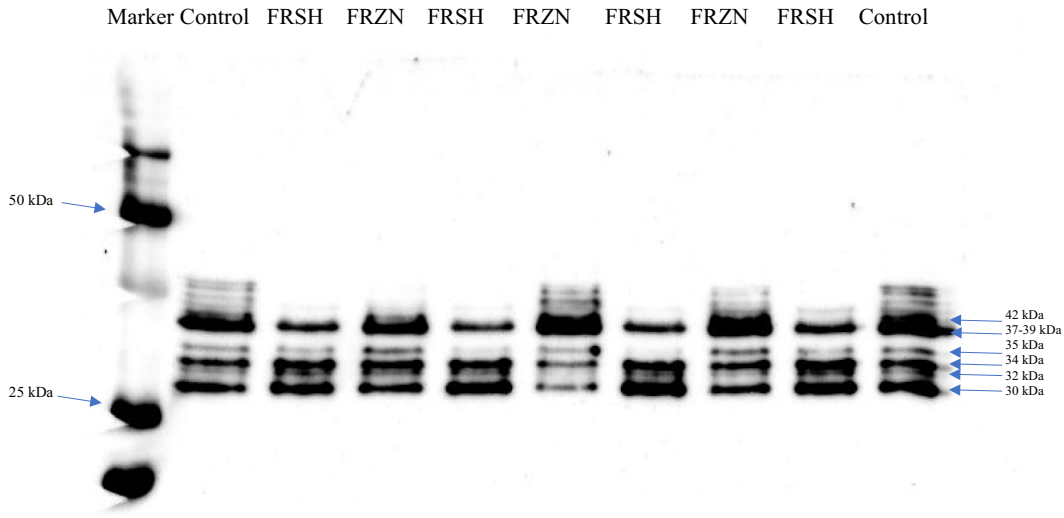

Figure 1. Representative troponin-T Western blot of whole muscle protein extracted from lamb *longissimus lumborum* stored fresh or frozen for 14 d.

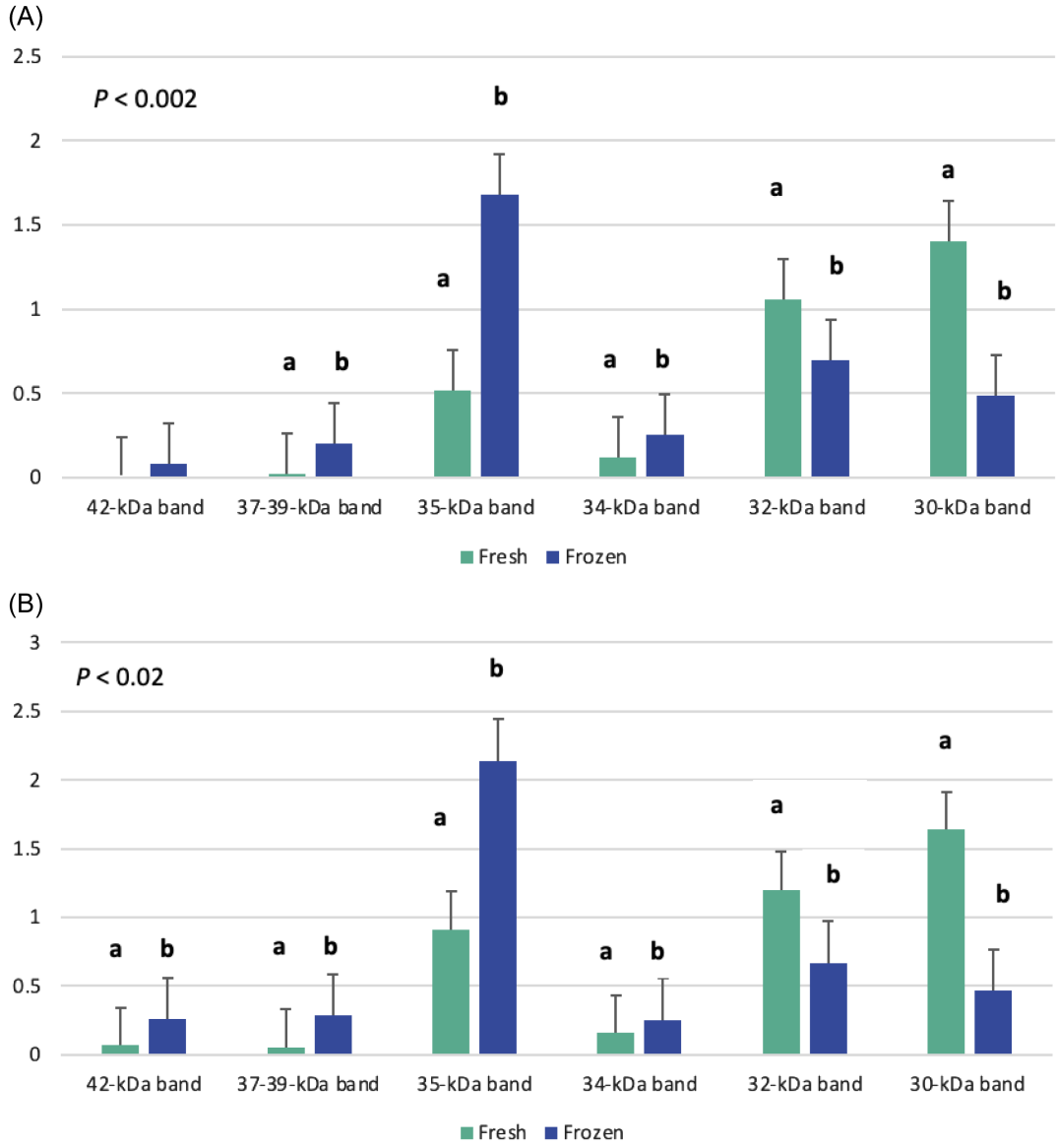

Figure 2. Effect of fresh and frozen storage[1] of lamb on troponin-T degradation[2] from two muscles. (A) *Longissimus lumborum* and (B) *Semimembranosus*. [1]Fresh samples were stored for 14 d in a 3°C cooler while frozen samples were stored for 13 d in a −18°C freezer. [2]Protein degradation values are relative abundance compared to the 30-kDa band of the pooled control set to a value of 1.0. [a,b]Means without common superscripts within groups differ significantly.

to drip out (Farouk et al., 2012). This hypothesis may likely explain the results observed in the present study as we did not allow for the FRZN treatment samples to age for any significant amount of time prior to freezing. It may be possible that the increased water loss in the FRZN treatment likely occurred due to the increase in formed drip channels and decrease in proteolysis.

Careful consideration is needed on the timing of freezing lamb in the postmortem period. In general, most processors do not allow for fresh aging of carcasses in the plant, but research has shown that 5 to7 d of aging can be beneficial for consumer palatability (Crouse and Koohmaraie, 1990; Kim et al., 2018). American lamb prides itself on fresh product, but given market conditions, times arise that freezing of cuts and later merchandising may be financially warranted.

Lipid oxidation

There was no treatment effect ($P > 0.05$) on MDA levels in either the LL or SM (Table 4). Research suggests that freezing in temperatures lower than −18°C allows for some water in meat to facilitate some primary lipid oxidation, which allows for secondary lipid oxidation to occur after thawing (Owen and Lawrie, 1975; Hansen et al., 2004; Leygonie et al., 2012).

Table 4. Least-squares means of the effect of fresh and frozen storage[1] of American lamb[2] *longissimus lumborum* and *semimembranosus* on malondialdehyde (MDA) levels (mg of MDA/kg of meat) as indicators of lipid oxidation

	Fresh	Frozen	SEM	*P* Value
Longissimus lumborum	9.20	9.58	0.41	0.36
Semimembranosus	9.71	9.80	0.58	0.89

[1]Vacuum packaged fresh samples ($n = 12$) were stored for 14 d at 3°C while frozen samples were stored for 13 d at −18°C.

[2]Dorset wether lambs, 6 to 7 mo of age, sourced from North Dakota State University sheep unit.

However, these studies were not performed in lamb meat. Muela et al. (2012) and Bueno et al. (2013) found that frozen storage of lamb may be acceptable for most consumers due to lack of significant changes in the meat during frozen storage that impact consumer acceptance.

Conclusions

Fresh lamb versus frozen treatments resulted in less water loss and inevitably increased end merchandisable product, as both FRSH-LL and FRSH-SM had less drip loss compared to FRZN-LL and FRZN-SM. Freezing lamb loin or leg for 13 d after an initial 24-h chill did not affect flavor in a consumer sensory panel. Sensory flavor characteristics were not distinguished differently by consumers, and this was supported by measurement of MDA levels indicating that lipid oxidation was not different between fresh and frozen lamb.

Fresh lamb loin, FRSH-LL, had higher overall like, tenderness, and juiciness scores compared with FRZN-LL, which could be due to increased protein degradation in FRSH because of aging that occurred at cooler temperatures and was curtailed at freezer temperatures. However, the same sensory results were not observed in the SM, although similar protein degradation occurred. Our research suggests that greater protein degradation may influence sensory attributes in the LL but not in the SM, which demonstrates that lamb legs may be frozen without negative effects on palatability whereas lamb loins should be kept fresh to offer the greatest opportunity for consumer satisfaction. However, retail yield of thawed lamb leg due to purge loss should be considered when making decisions on storage and marketing.

Literature Cited

AMSA. 2016. Research guidelines for cookery, sensory evaluation, and instrumental tenderness measurements of meat. Version 1.02, 2nd ed. Am. Meat Sci. Assoc., Champaign, IL.

Ballin, N. Z., and R. Lametsch. 2008. Analytical methods for authentication of fresh vs. thawed meat—A review. Meat Sci. 80:151–158. https://doi.org/10.1016/j.meatsci.2007.12.024.

Bueno, M., V. C. Resconi, M. M. Campo, J. Cacho, V. Ferreira, and A. Escudero. 2013. Effect of freezing method and frozen storage duration on odor-active compounds and sensory perception of lamb. Food Res. Int. 54:772–780. https://doi.org/10.1016/j.foodres.2013.08.003.

Choe, J. H., A. Stuart, and Y. H. B. Kim. 2016. Effect of different aging temperatures prior to freezing on meat quality attributes of frozen/thawed lamb loins. Meat Sci. 116:158–164. https://doi.org/10.1016/j.meatsci.2016.02.014.

Crouse, J. D., and M. Koohmaraie. 1990. Effect of freezing beef on subsequent postmortem aging and shear force. J. Food Sci. 55:573–574. https://doi.org/10.1111/j.1365-2621.1990.tb06819.x.

Devine, C. E., and A. E. Graafhuis. 1995. The basal toughness of unaged lamb. Meat Sci. 39:285–291. https://doi.org/10.1016/0309-1740(94)P1829-K.

Dubost, A., D. Micol, B. Meunier, C. Lethias, and A. Listrat. 2013. Relationships between structural characteristics of bovine intramuscular connective tissue assessed by image analysis and collagen and proteoglycan content. Meat Science 93:378–386. https://doi.org/10.1016/j.meatsci.2012.09.020.

Farouk, M. M., M. Beggan, S. Hurst, A. Stuart, P. M. Dobbie, and A. E. D. Bekhit. 2007. Meat quality attributes of chilled venison and beef. J. Food Quality 30:1023–1039. https://doi.org/10.1111/j.1745-4557.2007.00175.x.

Farouk, M. M., N. M. Mustafa, G. Wu, and G. Krsinic. 2012. The "sponge effect" hypothesis: An alternative explanation of the improvement in the waterholding capacity of meat with ageing. Meat Sci. 90:670–677. https://doi.org/10.1016/j.meatsci.2011.10.012.

Farouk, M., E. Wiklund, A. Stuart, and P. Dobbie. 2009. Ageing prior to freezing improves waterholding capacity in beef and venison. Proceedings of 55th International Congress of Meat Science and Technology, Copenhagen, Denmark, 16–21 August.

Hansen, E., D. Juncher, P. Henckel, A. Karlsson, G. Bertelsen, and L. H. Skibsted. 2004. Oxidative stability of chilled pork chops following long term freeze storage. Meat Sci. 68:497–484. https://doi.org/10.1016/j.meatsci.2004.05.002.

Huff-Lonergan, E., T Mitsuhashi, F. C. Parrish Jr., and R. M. Robson. 1996. Sodium dodecyl sulfate-polyacrylamide gel electrophoresis and western blotting comparisons of purified myofibrils and whole muscle preparation for evaluating titin and nebulin in postmortem bovine muscle. J. Anim. Sci 74:779–785. https://doi.org/10.2527/1996.744779x.

Joo, S. T., R. G. Kauffman, B. C. Kim, and G. B. Park. 1999. The relationship of sarcoplasmic and myofibrillar protein solubility to colour and water-holding capacity in porcine longissimus muscle. Meat Sci. 52:291–297. https://doi.org/10.1016/S0309-1740(99)00005-4.

Kim, Y. H. B., M. Frandsen, and K. Rosenvold. 2011. Effect of ageing prior to freezing on colour stability of ovine longissimus muscle. Meat Sci. 88:332–337. https://doi.org/10.1016/j.meatsci.2010.12.020.

Kim, H-W., J-H. Kim, J-K. Seo, D. Setyabrata, and Y. H. B. Kim. 2018. Effects of aging/freezing sequence and freezing rate on meat quality and oxidative stability of pork loins. Meat Sci. 139:162–170. https://doi.org/10.1016/j.meatsci.2018.01.024.

Kim, Y. H. B., G. Luc, and K. Rosenvold. 2013. Pre rigor processing, ageing, and freezing on tenderness and colour stability of lamb loins. Meat Sci. 95:412–418. https://doi.org/10.1016/j.meatsci.2013.05.017.

Lambooij, M. S., J. Veldwijk, P. van Gils, M-J.J. Mangen, E. Over, A. Suijkerbuijk, J. Polder, G. A. de Wit, and M. Opsteegh. 2019. Consumers' preferences for freezing of meat to prevent toxoplasmosis—A stated preference approach. Meat Sci. 149:1–8. https://doi.org/10.1016/j.meatsci.2018.11.001.

Leygonie, C., T. J. Britz, and L. C. Hoffman. 2012. Impact of freezing and thawing on the quality of meat: Review. Meat Sci. 91:93–98. https://doi.org/10.1016/j.meatsci.2012.01.013.

Li, S., X. Li, Q. Ma, Z. Wang, F. Fang, and D. Zhang. 2022. Consumer preference, behaviour and perception about lamb meat in China. Meat Sci. 192:1–7. https://doi.org/10.1016/j.meatsci.2022.108878.

Liang, C., D. Zhang, X. Zheng, X. Wen, T. Yan, Z. Zhang, and C. Hou. 2021. Effects of different storage temperatures on the physicochemical properties and bacterial community structure of fresh lamb meat. Food Science of Animal Resources 41:509–526. https://doi.org/10.5851/kosfa.2021.e15.

MacBride, M. A., and F. C. Parrish Jr. 1977. The 30,000 Dalton component of tender bovine longissimus muscle. J. Food Sci. 42:1627–1629. https://doi.org/10.1111/j.1365-2621.1977.tb08442.x.

Melody, J. L., S. M. Lonergan, L. J. Rowe, T. W. Huiatt, M. S. Mayes, and E. Huff-Lonergan. 2004. Early postmortem biochemical factors influence tenderness and water-holding capacity of three porcine muscles. J. Anim. Sci. 82:1195–1205. https://doi.org/10.2527/2004.8241195x.

Muela, E., P. Monge, C. Sañudo, M. M. Campo, and J. A. Beltrán. 2015. Meat quality of lamb frozen stored up to 21 months: Instrumental analyses on thawed meat during display. Meat Sci. 102:35–40. https://doi.org/10.1016/j.meatsci.2014.12.003.

Muela, E., P. Monge, C. Sanudo, M. M. Campo, and J. A. Beltran. 2016. Sensory quality of lamb following long-term frozen storage. Meat Sci. 114:32–37. https://doi.org/10.1016/j.meatsci.2015.12.001.

Muela, E., C. Sanudo, M. M. Campo, I. Medel, and J. A. Beltran. 2010. Effect of freezing method and frozen storage duration on instrumental quality of lamb throughout display. Meat Sci. 84:662–669. https://doi.org/10.1016/j.meatsci.2009.10.028.

Muela, E., C. Sanudo, M. M. Campo, I. Medel, and J. A. Beltran. 2012. Effect of freezing method and frozen storage duration on lamb sensory quality. Meat Sci. 90:209–215. https://doi.org/10.1016/j.meatsci.2011.07.003.

Olson, D. G., F. C. Parrish Jr., and M. H. Stromer. 1976. Myofibril fragmentation and shear resistance of three bovine muscles during postmortem storage. J. Food Sci. 41:1036–1041. https://doi.org/10.1111/j.1365-2621.1976.tb14384.x.

Owen, J. E., and R. A. Lawrie. 1975. The effect of an artificially induced high pH on the susceptibility of minced porcine muscle to undergo oxidative rancidity under frozen storage. Int. J. Food Sci. Tech. 10:169–180. https://doi.org/10.1111/j.1365-2621.1975.tb00019.x.

Redden, R., E. Sanko, R. Ehrhardt, and C. Hiemke. 2018. Seasonality of the US lamb industry. American Lamb Board. 1–17.

Smith, G. C., C. W. Spaeth, Z. L. Carpenter, G. T. King, and K. E. Hoke. 1968. The effects of freezing, frozen storage conditions and degree of doneness on lamb palatability characteristics. J. Food Sci. 33:19–24. https://doi.org/10.1111/j.1365-2621.1968.tb00876.x.

Stenberg, E., K. Arvidsson-Segerkvist, A. H. Karlsson, A. Olafsdottir, O. P. Hilmarsson, Gudjonsdottir, and G. Thorkelsson. 2022. A comparison of fresh and frozen lamb meat—Differences in technological meat quality and sensory attributes. Animals 12:2830. https://doi.org/10.3390/ani12202830.

Tschirhart-Hoelscher, T. E., B. E. Baird, D. A. King, D. R. McKenna, and J. W. Savell. 2006. Physical, chemical, and histological characteristics of 18 lamb muscles. Meat Sci. 73:48–54. https://doi.org/10.1016/j.meatsci.2005.10.015.

Ufer, D., A. M. Countryman, and A. Muhammad. 2020. How important are product attributes for US lamb imports? Int. Food Agribus. Man. 23:411–423. https://doi.org/10.22434/IFAMR2019.0204.

USDA-ERS. 2012. Lamb/mutton production expected to show strength leading up to the Spring religious holidays. United States Department of Agriculture-Economic Research Service. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=75628. (Accessed September 21, 2022).

Wang, K. 1982. Purification of titin and nebulin. Method. Enzymol. 85:264–274. https://doi.org/10.1016/0076-6879(82)85025-8.

Watkins, P. J., D. Frank, T. K. Singh, O. A. Young, and R. D. Warner. 2013. Sheepmeat flavor and the effect of different feeding systems: A review. J. Agr. Food Chem. 61:3561–3579. https://doi.org/10.1021/jf303768e.

Zhang, S. X., M. M. Farouk, O. A. Young, K. J. Wieliczko, and C. Podmore. 2005. Functional stability of frozen normal and high pH beef. Meat Sci. 69:765–772. https://doi.org/10.1016/j.meatsci.2004.11.009.