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Combined Impacts of Initial Freezing Rate and Thawing/Cooking Conditions on Physicochemical and Textural Properties of Pork Patties

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Abstract: This study aimed to investigate the combined impact of freezing rates (slow freezing rate [SFR]: 0.06°C/min; fast freezing rate [FFR]: 0.45°C/min; ultra-fast freezing rate [UFR]: 1.20°C/min) and thawing methods (cooking from frozen state [UTC]; water immersion in a 25°C water bath [WAT]; refrigerator at 2°C [RFT] until the core temperature reaches 2°C) on the physicochemical and texture characteristics of cooked pork patties. In 3 independent batches, *biceps femoris* muscles from 6 pork carcasses were ground to manufacture pork patties, which were assigned to 3 freezing conditions. The patties were thawed and cooked on the electric grill until they reached a core temperature of 72°C. An increase in the freezing rate increased moisture content and lowered water loss characteristics ($P < 0.05$), resulting in the reduced total loss (sum of freezing, thawing, and cooking losses) of cooked patties ($P < 0.05$). Thawing methods only affected the total loss in cooked patties, in which UTC patties had a lower total loss than RFT and WAT ($P < 0.05$), but no difference was found between RFT and WAT ($P > 0.05$). Instrumental color attributes were not affected by either freezing or thawing conditions ($P > 0.05$). Fast freezing significantly decreased hardness values, and accelerated thawing (WAT) also resulted in lower hardness values compared with other thawing methods ($P < 0.05$). Reduction in diameter during cooking was only affected by freezing rate ($P < 0.05$), in which patties assigned to FFR and UFR had more reduction in diameter than SFR patties. Thawing methods only affected lipid oxidation, in which WAT had lower 2-thiobarbituric acid reactive substance values than UTC and RFT ($P < 0.05$). These results indicate that the freezing rate would have more predominant impacts on cooked pork patties, in which FFR improved moisture contents and minimized freezing/thawing-induced water loss of cooked patties. Although thawing conditions have some minor impacts, no differences between UTC (direct cooking without thawing) patties and other frozen/thawed-then-cooked patties (RFT and WAT) in cooking loss and most texture profile attributes were found. Our results suggest that fast freezing can improve the overall quality of cooked patties, whereas combined impacts with thawing would be practically less meaningful.

Key words: freezing rate, thawing method, cooked pork patty, physicochemical characteristics, textural properties
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Introduction

Meat freezing is one of the most common and widely adopted preservation methods. Depending upon various freezing conditions (e.g., freezing temperatures, packaging conditions, and meat product types, etc.), it can extend the shelf life of highly perishable meat products from several weeks to months. However, it has been well documented that freezing may adversely impact meat quality attributes because of cryodamage on muscle cells (Leygonie et al., 2012a). The damaged muscle tissue by ice crystal formation causes physicochemical and structural changes, reducing the final product's quality, particularly inducing excessive purge/thaw loss (Leygonie et al., 2012a). Extensive studies, however, have shown that an increase in freezing rate can diminish the cryodamage-related quality defects in meat and meat products by resulting in the formation of more uniformly distributed and smaller ice crystals located both inside and outside cells (Li et al., 2018, 2020; Balan et al., 2019; Tuell et al., 2020). Regarding frozen meat patty concerns, several studies reported the effect of freezing rate on the physicochemical and quality attributes of the patty-type products (Berry and Leddy, 1989; Tuell et al., 2020).

Besides freezing, thawing is another important factor affecting quality attributes of frozen/thawed meat products. Several studies have shown that thawing methods can influence meat quality attributes of different meat products, such as beef steaks (Eastridge and Bowker, 2011), pork loins (Ngapo et al., 1999; Mortensen et al., 2006), chicken breast (Zhang et al., 2021), and ostrich fan fillet (Leygonie et al., 2012b). However, there are inconsistent results between studies related to the effect of thawing rates on meat quality characteristics (drip loss, in particular), in which positive impacts of fast thawing (Ambrosiadis et al., 1994; Ngapo et al., 1999), adverse impacts of fast thawing (Ngapo et al., 1999), or no relationship (Empey, 1993) between thawing rates and drip loss were reported. These discrepancies may be attributed to the fact that most studies only focused on each independent freezing or thawing effect rather than considering the possible combined impacts of both freezing and thawing rates on meat quality. Because thawing is an essential process for frozen meat, it is reasonable to question whether the initial freezing rates and subsequent thawing methods should be evaluated together to gain a more comprehensive understanding and practical implications.

However, no published information is available determining the potential combined influences of freezing rate and thawing methods on quality characteristics for meat patty products. Furthermore, cooking after complete thawing is a common handling procedure for frozen meat. However, in the fast-food sector, it is sometimes necessary to cook frozen patties directly without thawing. Meat patties are one of the most popular meat products worldwide. The market size of packaged burgers was valued at USD 3.02 billion in 2019 and is expected to grow at an annual rate of 8.0% from 2020 to 2027 (Grand View Research, 2020). Additionally, the proportion of frozen patties was more than 80% in 2019 and is still increasing (Grand View Research, 2020). Given the popularity and practicality of the frozen meat patty, it is crucial to understand the combined impacts of freezing and thawing methods on quality attributes of a meat patty. Therefore, the objective of the study was to determine the effect of freezing rate and thawing method on meat quality and physicochemical attributes of cooked pork patties.

Materials and Methods

Materials and sample preparation

Hind portions of 6 pork carcasses were obtained at 2 d postmortem. The *biceps femoris* muscles were collected and trimmed by removing connective tissues and excess fats. The *biceps femoris* muscles were stored at −40°C until patty manufacturing. The *biceps femoris* muscles from 2 different animals were ground by using a meat grinder (M12FS, Torrey, Monterrey, NL, Mexico) with a 9.5-mm plate. In each independent batch, a total of 72 ground pork patties was formulated with 100% ground pork muscle and formed using a round shape patty maker (11.5 cm × 7 cm), and the weight and diameter of the pork patties were approximately 80 g and 10.5 cm, respectively. The ground pork patties were randomly assigned into 3 different freezing groups (24 patties per freezing treatment). The patties in each group were then subdivided into 3 different thawing groups, resulting in 8 ground pork patties per combination of treatments as pseudo replicates. The raw material processing, including grinding and patty formulations and treatment allocations, was repeated 3 times on different days.

Freezing and thawing treatments

For the freezing and thawing treatment allocations, the patties were covered by wax paper on both top and bottom sides and then immediately subjected to the allocated freezing treatments. The patties assigned to slow freezing rate (SFR) were placed into a commercial −20°C freezer. Fast and ultra-fast freezing rates were conducted by placing the covered patties in a liquid nitrogen freezing cabinet (Cabinet Freezer, RS Cryo Equipment, Manteno, IL) set −50°C for fast freezing rate (FFR) and −80°C for ultra-fast freezing rate (UFR) as operating temperatures. Then, the samples were taken out from the freezer when the internal core temperature reached −20°C. The internal temperature of samples was monitored by using the thermocouple temperature recorder (OctTemp2000, MadgeTech, Warner, NH) with MadgeTech 4 software. All frozen samples were vacuum packed (4 patties per package) and then stored in the −20°C conventional freezer chamber for 3 to 4 wk. For thawing, the frozen patties were subjected to different thawing methods: (1) refrigerator at 2°C (RFT), (2) submerging in a 25°C water bath (WAT) (89032-206, VWR, Radnor, PA) (WAT), and (3) unthawing, but direct cooking (cooking from frozen state [UTC]). The freezing rates and thawing rates of patties assigned to different freezer types and thawing methods were expressed in Figure 1. For thawing process, thawing rate was obtained as the ratio of radius curvature to the thawing time to traverse the temperature range from −20°C to 2°C. Before cooking, the thawed patties using water immersion were placed in a refrigerated room (at 2°C) for 1 h to fix the core temperature consistently. All patties were cooked immediately on the electric grill (Farberware, Walter Kidde and Co., Bronx, NY) at 150°C to reach 72°C core temperature, and the cooking time of each sample was recorded.

Proximate analysis and pH

Proximate composition of cooked samples was analyzed according to AOAC (2006). The pH of cooked patties was analyzed in triplicate using an electronic pH meter (Sartorius Basic Meter PB-11, Sartorius AG, Goettingen, Germany). The pH meter was calibrated with pH 4 and 7 standard solutions.

Instrumental color

The cooked patties were allowed to equilibrate to room temperature for 1 h. The cooked patty was sliced horizontally in order to assess the internal color. Surface and internal colors of cooked patties were measured using a HunterLab MiniScan EZ colorimeter (HunterLab, Reston, VA) equipped with 25-mm diameter of aperture size. The light source and observer were A and standard 10°, respectively. The color measuring process was conducted by the AMSA Color Guidelines (King et al., 2023). Color values were expressed as Commission Internationale de 1΄Eclairage (CIE) L^* (lightness), CIE a^* (redness), and CIE b^* (yellowness). The values were collected from 3 random spots each cooked patty, and 4 patties were used for each treatment combination.

Freezing loss

The freezing loss was estimated by measuring the weight difference of pork patties before and immediately after freezing. The calculation formula is as follows:

$$\text{Freezing loss (\%)} = (\text{weight of unfrozen pork patty} - \text{weight of frozen pork patty}) / (\text{weight of unfrozen pork patty}) \times 100$$

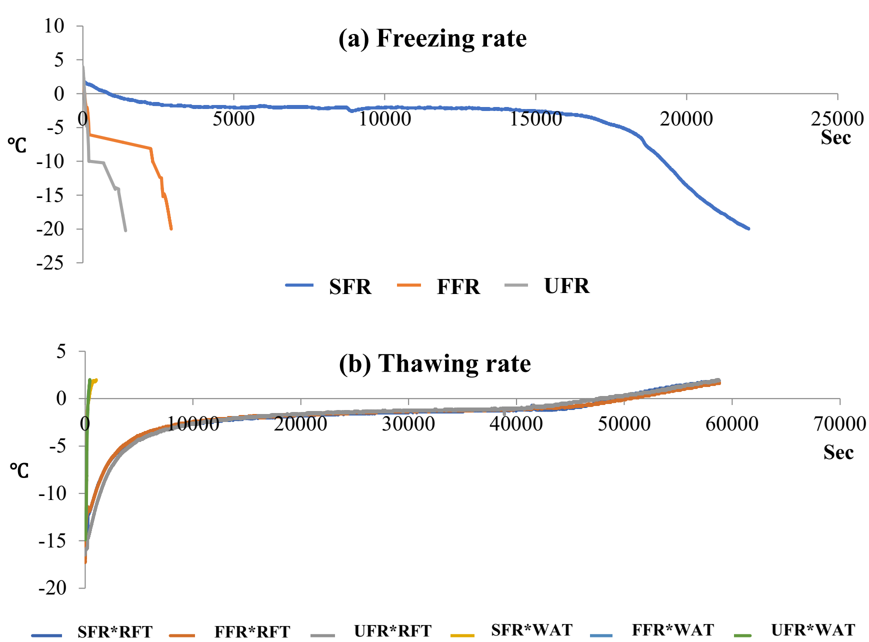

Figure 1. The temperature monitored from different freezing and thawing rates according to freezer type and thawing method. Freezing rate: FFR (fast freezing rate) 0.45°C/min; SFR (slow freezing rate), 0.06°C/min; UFR (ultra-fast freezing rate) 1.20°C/min. Thawing methods: RFT, refrigerator at 2°C; UTC, cooking from frozen state; WAT, water immersion at 25°C.

Thawing loss

The frozen pork patties were weighed before being assigned to different thawing methods. Then, after thawing, the patties were reweighed to estimate thawing loss. The calculation formula is as follows:

$$\text{Thawing loss (\%)} = (\text{weight of frozen pork patty} - \text{weight of thawed pork patty}) / (\text{weight of frozen pork patty}) \times 100$$

Cooking loss

The cooking loss was determined by measuring the weight difference between uncooked and cooked pork patty. The calculation formula is as follows:

$$\text{Cooking loss (\%)} = (\text{weight of uncooked pork patty} - \text{weight of cooked pork patty}) / (\text{weight of uncooked pork patty}) \times 100$$

Total loss

Total loss (%) was estimated according to the sum of freezing, thawing, and cooking losses.

Reduction in diameter and change in thickness

The reduction in diameter was determined by following the procedure described by Berry et al. (1993). Also, the change in thickness (expressed with absolute value) was determined by measuring the thickness difference before and after cooking. Each measurement value was estimated by the following equations:

$$\text{Reduction in diameter (\%)} = (\text{uncooked pork patty diameter} - \text{cooked pork patty diameter}) / (\text{uncooked pork patty diameter}) \times 100$$

$$\text{Change in thickness (mm)} = |\text{uncooked pork patty thickness} - \text{cooked pork patty thickness}|$$

Texture profile analysis

Texture profile analysis was conducted in quadruplicate of each cooked patty according to the method of Bourne et al. (1978) using a TA.XT Plus Texture Analyzer (Stable Micro Systems, Surrey, UK) equipped with an aluminum cylindrical probe (5.08 cm diameter and 20 mm height). A twice compression (70%, 14 mm distance) cycle test was performed. The conditions of texture profile analysis were as follows: pretest speed 1.0 mm/s, post-test speed 5.0 mm/s, and test speed 5.0 mm/s. The texture traits for hardness (*N*), springiness, cohesiveness, gumminess, and chewiness were determined by Bourne et al. (1978).

Thiobarbituric acid reactive substance (2-thiobarbituric acid) measurement

Thiobarbituric acid reactive substance (TBARS) measurement was conducted according to Ahn et al. (1998) method with a few modifications. Five grams of sample were homogenized with 15 mL of distilled water and 50 μL of 10% butylated hydroxyl anisole in 90% ethanol. One milliliter of homogenates was mixed with 2 mL of 2-thiobarbituric acid (TBA) reagent (20 mM TBA/15% trichloroacetic solution). The mixture was heated for 15 min in an 80°C water bath. The heated samples were placed in cold water and then were centrifuged at 2,000 × *g* for 10 min at 25°C. The supernatant was filtered through Whatman filter paper 4 (Cytiva, Marlborough, MA). The absorbance of samples was recorded at 531 nm. The TBA value was calculated by using the molecular extinction coefficient ($1.56 \times 10^5\ M^{-1} \cdot cm^{-1}$), and the data were expressed as malondialdehyde (MDA) milligram/kilogram sample.

Statistical analysis

The experiment was factorial designed as a randomized complete block design in which a full factorial assignment of 3 freezing rates × 3 thawing methods was used. A total of 3 independent batches was used for the statistical analysis ($n = 3$). Data analysis was conducted using the general linear model procedure of SAS statistics (v. 9.4, SAS Institute, Cary, NC) for two-way analyses of variance to determine the statistical differences according to freezing rates and thawing methods and their interaction ($P < 0.05$) by using a Tukey test. The independent batch was considered as a random variable.

Results and Discussion

Freezing and thawing rate profile

Freezing and thawing rates of pork patties subjected to 3 freezing conditions (SFR, slow; FFR, fast; UFR, ultra-fast) and 3 thawing methods (RFT, refrigeration; WAT, submerging in water; UTC, unthawed/direct cooking) were monitored (Figure 1). The freezing time to traverse the critical freezing point (*Tc*) from

−1°C to −7°C, at which most of the ice crystallization (>80%) occurs (Kiani and Sun, 2011), was 275 min (SFR of 0.02°C/min), 13 min (FFR of 0.46°C/min), and 2.83 min (UFR of 2.12°C/min), respectively. This result confirms that different freezing rates were achieved through the current experimental setting for freezing conditions. *Tc* has been considered as an initial critical indicator to determine the extent of ice crystal formation, location, and subsequent cryodamage (Grujic et al., 1993; Ngapo et al., 1999; Kiani and Sun, 2011).

Thawing rates were calculated based on thawing time from −20°C to 2°C. Regardless of different initial freezing rates, thawing times of patties assigned to RFT and WAT were approximately 970 to 980 min (0.02°C/min) and 10 to 15 min (1.76°C/min) on average, respectively. Thus, the defrosting of the samples could be predominantly affected by heat transfer rates induced by different thawing temperatures (RTC, 2°C and WTC, 25°C) irrespective of initial freezing rates of patties.

Table 1. Proximate composition of pork patties treated by different freezing rates and thawing methods

Effects	Moisture (%)	Protein (%)	Fat (%)	Ash (%)
Freezing rate effect				
SFR	62.7[b]	30.3[a]	4.96	2.03
FFR	63.6[a]	29.3[b]	5.20	1.95
UFR	63.8[a]	29.2[b]	4.93	2.03
SEM[1]	0.52	0.49	0.16	0.03
Thawing method effect				
UTC	64.0[x]	29.5	4.58	1.90[y]
RFT	63.5[x]	29.5	4.90	2.13[x]
WAT	62.6[y]	29.8	5.61	1.98[y]
SEM	0.26	0.59	0.44	0.03
Significance of *P* value				
Freezing rate (*F*)	0.018	0.002	0.425	0.314
Thawing methods (*T*)	0.013	0.867	0.587	<0.001
Interaction (*F* × *T*)	0.673	0.782	0.745	0.114

Note: Freezing rate: FFR (fast freezing rate), 0.45°C/min; SFR (slow freezing rate), 0.06°C/min; UFR (ultra-fast freezing rate), 1.20°C/min. Thawing methods: RFT, refrigerator at 2°C; UTC, cooking from frozen state; WAT, water immersion at 25°C.

[a,b]Means with different lowercase letters differ significantly ($P < 0.05$).

[x–z]Means with different lowercase letters differ significantly ($P < 0.05$).

[1]Standard error of the means.

Proximate composition

The moisture content of cooked pork patties was affected by freezing rates ($P < 0.05$) and thawing conditions ($P < 0.05$), but no interaction between freezing and thawing rates was found ($P > 0.05$; Table 1). The faster freezing rate increased the percent moisture content, wherein UFR and FFR had greater moisture content than SFR ($P < 0.05$), but no difference between UFR and FFR was found ($P > 0.05$). Similar observations were reported by Kim et al. (2018) and Tuell et al. (2020), in which fast freezing resulted in higher moisture contents in pork loins and fresh pork patties compared with the SFR counterparts, thus suggesting the freezing rate could affect the moisture content of frozen/thawed pork patties.

It has been well established that freezing results in nucleation and crystallization of moisture in muscle, which causes physicochemical damage to the muscle structure through distortion and disruption of muscle fibers upon thawing (Leygonie et al., 2012b). Because such damaged meat has various disadvantages, namely excessive water loss in particular (Leygonie et al., 2012a; Lu et al., 2022), controlling the extent of ice crystallization plays a crucial role in affecting the final quality of frozen/thawed meat (Dang et al., 2021). Also, the decrease in moisture contents of slow frozen patties could be attributed to the increase in the extent of evaporation during freezing, as shown by the initial freezing loss result (Table 2), which will be discussed in more detail in the next (water loss characteristics) section.

In terms of thawing methods and their impacts on the moisture content of pork patties, UTC and RFT had a higher moisture content than WAT ($P < 0.05$). Moreover, no difference between UTC and RFT patties in the moisture content was found ($P > 0.05$). This result is in agreement with the findings from Kim et al. (2013), in which the frozen beef loins that were thawed in a refrigerator (4°C) showed approximately 2.5% higher moisture content than beef loins thawed in cold water (15°C) and at room temperature (25°C). Although there is limited information in the literature about which mechanisms' thawing rates would affect the moisture contents of frozen/thawed meat, the moisture contents might be attributed to the extent of reabsorption of extracellular water by muscle fibers. Gonzalez-Sanguinetti et al. (1985) proposed that thawing conditions (and subsequent thawing rates) would influence the water activity of extracellular water upon thawing, which in turn could affect the extent of water migration from extracellular space to intracellular space and subsequent water reabsorption by muscle fibers. Thus, an increase in the thawing rate may shorten the time of the water reabsorption phenomenon, leading to more exudate release and less water content. Therefore, in the present study, the less water content in the patties assigned to WAT (fast thawing) may be attributed to relatively less extracellular water reabsorption compared with the patties assigned to RFT (slow thawing). However, it is of interest to note that patties assigned to UTC (no thawing but direct cooking) also had higher water content than WAT ($P < 0.05$). This result will be discussed in more detail in the next section because it would likely be related to freeze/thaw loss characteristics.

In terms of protein and ash compositions, the cooked pork patties were significantly affected by the freezing rate and thawing method, respectively, wherein SFR showed the highest protein content and RFT showed the lowest ash ratio ($P < 0.05$). This observation could be attributed to a change in the ratio of moisture in the cooked pork patty by the freezing and thawing process, which in turn would result in a different ratio of protein to ash accordingly.

pH and water-holding capacity

The pH range of cooked patty samples that were frozen and thawed was 5.76 to 5.80 (Table 2). The pH was not affected by freezing rate, thawing method, or their interaction ($P > 0.05$). Farouk et al. (2004) reported a similar result that the freezing rates did not impact the pH of meat.

The freezing rate affected the initial weight loss of frozen patties as shown in Table 2, in which the patties assigned to SFR had greater weight loss compared with the patties assigned to faster freezing conditions (FFR and UFR, $P < 0.05$). However, no difference in freezing loss was found between FFR and UFR ($P > 0.05$). Given that the freezing loss was determined by simply measuring weight difference immediately after freezing, the greater freezing loss of SFR would likely be attributed to more moisture evaporation because of longer air exposure/freezing time (Figure 1), as previously discussed. Thawing loss itself, on the other hand, was not affected by prior freezing rates, thawing methods, or their interaction ($P > 0.05$). Also, cooking loss was not affected by any of the treatments and their interaction ($P > 0.05$). However, when combining the freezing/thawing loss and cooking loss of samples together as total loss, there was a significant freezing rate effect in which SFR resulted in greater total loss compared with FFR and UFR ($P < 0.05$). The higher total loss of slow frozen patties was mainly due to

Table 2. pH and water loss characteristics of pork patties treated by different freezing rate and thawing method

Effects	pH	Freezing loss (%)	Thawing loss (%)	Cooking loss (%)	Total loss (%)
Freezing rate effect					
SFR	5.79	3.2[a]	0.8	24.3	28.0[a]
FFR	5.77	1.7[b]	0.7	24.5	26.9[b]
UFR	5.77	1.4[b]	0.8	24.0	26.2[b]
SEM[1]	0.01	0.02	0.70	1.23	1.32
Thawing method effect					
UTC	5.78	—	—	22.6	22.6[y]
RFT	5.78	—	0.6	25.6	26.2[x]
WAT	5.77	—	0.9	24.6	25.5[x]
SEM	0.01	—	0.07	1.42	1.49
Freezing rate (*F*)	0.415	<0.001	0.855	0.619	0.001
Thawing methods (*T*)	0.621	—	0.284	0.191	<0.001
Interaction ($F \times T$)	0.567	—	0.346	0.382	0.353

Note: Freezing rate: FFR (fast freezing rate), 0.45°C/min; SFR (slow freezing rate), 0.06°C/min; UFR (ultra-fast freezing rate), 1.20°C/min. Thawing methods: RFT, refrigerator at 2°C; UTC, cooking from frozen state; WAT, water immersion at 25°C.

[a,b]Means with different lowercase letters differ significantly ($P < 0.05$).

[x–z]Means with different lowercase letters differ significantly ($P < 0.05$).

[1]Standard error of the means.

Table 3. Cooking properties of pork patties treated by different freezing rate and thawing method

Effects	Cooking time (min)	Reduction in diameter (%)	Change in thickness (mm)
Freezing rate effect			
SFR	8.9	16.7[b]	1.4
FFR	9.3	18.0[a]	1.4
UFR	9.3	17.8[a]	1.6
SEM[1]	0.5	0.60	0.24
Thawing method effect			
UTC	10.5[x]	18.0	0.6[y]
RFT	8.7[y]	17.1	1.7[x]
WAT	8.4[y]	17.4	2.1[x]
SEM	0.69	0.63	2.60
Significance of *P* value			
Freezing rate (*F*)	0.137	0.010	0.456
Thawing methods (*T*)	0.036	0.312	<0.001
Their interaction ($F \times T$)	0.619	0.104	0.429

Note: Freezing rate: FFR (fast freezing rate), 0.45°C/min; SFR (slow freezing rate), 0.06°C/min; UFR (ultra-fast freezing rate), 1.20°C/min. Thawing methods: RFT, refrigerator at 2°C; UTC, cooking from frozen state; WAT, water immersion at 25°C.

[a,b]Means with different lowercase letters differ significantly ($P < 0.05$).

[x,y]Means with different lowercase letters differ significantly ($P < 0.05$).

[1]Standard error of the means.

the increase in freezing loss itself rather than thawing and cooking losses. This observation confirms that fast freezing results in a positive effect on the water-holding characteristics. Zhang and Ertbjerg (2019) also reported that the fast freezing of pork loin resulted in higher water-holding capacity (WHC) and lower purge loss compared with the slow frozen counterpart. Also, Añón and Carvelo (1980) reported the relevance of the freezing rate and WHC, in which an increase in freezing rates results in a decrease in the amount of exudate. Our results also suggest that initial freezing rate may play a major role in controlling water loss characteristics of meat, whereas thawing may affect the final water contents of the products. In fact, Gonzalez-Sanguinetti et al. (1985) reported that freezing rate influences the WHC of meat by determining the size and localization (either intracellular or extracellular) of ice crystals in muscle fibers, whereas thawing conditions may affect the extent of extracellular water reabsorption and thus final water content.

It is of interest to note that patties assigned to direct cooking without thawing (UTC) did not differ in cooking loss ($P > 0.05$) but did differ significantly in total loss compared with patties assigned to RFT and WAT ($P < 0.05$). In fact, UTC not only showed a total loss about 3% lower than RFT and WAT but also had numerically lower cooking loss. These results could in turn likely result in the greater water content in UTC, as discussed in the previous section. One may expect that direct cooking of frozen patties may induce an increase in cooking loss because of the direct heat transfer of frozen meat. However, our results show that direct cooking of unthawed patties resulted in numerically lower cooking loss and significantly lower than the total loss of frozen/thawed–then cooked patties (RFT and WAT). This result could be attributed to the fact that patties assigned to thawing prior to cooking led to subsequent purge loss upon thawing.

Cooking properties

Cooking time of patties was only affected by thawing conditions ($P < 0.05$), wherein UTC took more time to cook to the target temperature than RFT and WAT (10.9 min versus 8.4 to 8.7 min), as expected. This observation is highly anticipated because the longer cooking time of UTC can be explained by a difference of initial temperatures between unthawed and thawed samples (approximately −20°C versus 2°C).

Reduction in diameter during cooking was only affected by freezing rate ($P < 0.05$), wherein patties assigned to FFR and UFR had more reduction in diameter than SFR patties. The thawing method and interaction between the freezing rate and thawing method had no impact on diameter reduction ($P > 0.05$). Diameter reduction is a phenomenon in which the diameter or thickness is changed mainly because of the release of water or fat among the components of a product (Tekin et al., 2010; Soltanizadeh and Ghiasi-Esfahani, 2015). In addition, the contraction caused by denaturation or aggregation of muscle fiber protein causes a decrease in the space between the filaments, thereby resulting more release of free water upon cooking and subsequent reduction in diameter (Leygonie et al., 2012a).

Subsequent change in thickness of patties upon cooking was only affected by thawing conditions ($P < 0.05$). Currently, there is no published research related to the thawing method for the change in thickness of meat patties. However, the present result may be related to the changes in density of patties upon cooking. When the patty is being cooked, it leads to moisture and fat release, which would result in the formation of pores and subsequent changes in the density of the patties (Troutt et al., 1992; Pan and Singh, 2001). Because thawed patties had a higher total loss than frozen patties (UTC), thawing may have caused more porosity. In addition, Du et al. (2016) stated that cooked meat can be considered a multiphase system, such as gas-liquid-solid systems, in which the mass transfer occurs during cooking. Therefore, it can be considered that thawed patties had more changes in thickness than frozen patties with direct cooking because of the formation of relatively more pores and the mass transfer during heating (Shi et al., 2021). Furthermore, more reduction in the diameter of patties assigned to FFR and UFR compared with SFR patties could be partially supported by the change in thickness results, wherein a higher change in thickness trend of FFR and UFR patties compared with SFR was found.

Instrumental color properties

Surface and internal color characteristics (CIE L^*, a^*, and b^*) of cooked patties were present in Table 4. Freezing rates as well as thawing methods did not affect color characteristics of cooked patties ($P > 0.05$) except CIE L^*. FFR and UFR patties showed higher internal CIE L^* values of cooked patties than SFR ($P < 0.05$). This observation may be attributed to the increased moisture content and improved WHC because of the increase in freezing rate of FFR and UFR. Fernández-López et al. (2000) reported that the lightness of cooked products is affected by WHC. Also, abundant

Table 4. Surface and internal color of pork patties treated by different freezing rate and thawing method

Effects	Surface CIE L^*	Surface CIE a^*	Surface CIE b^*	Internal CIE L^*	Internal CIE a^*	Internal CIE b^*
Freezing rate effect						
SFR	59.82	4.55	18.05	62.21[b]	3.15	15.03
FFR	60.84	4.38	18.21	63.27[a]	3.18	15.10
UFR	60.83	4.44	17.95	63.64[a]	3.09	15.14
SEM[1]	1.02	0.32	0.67	0.47	0.13	0.32
Thawing method effect						
UTC	58.61	4.95	18.06	62.63	3.03	14.79
RFT	58.64	5.22	19.95	63.30	3.11	15.14
WAT	60.63	4.48	18.76	63.36	3.28	15.34
SEM	1.03	0.32	0.66	0.52	0.12	0.32
Significance of *P* value						
Freezing rate (*F*)	0.45	0.844	0.717	0.004	0.697	0.958
Thawing methods (*T*)	0.479	0.780	0.466	0.756	0.499	0.543
Their interaction ($F \times T$)	0.286	0.879	0.714	0.485	0.762	0.438

Note: Freezing rate: FFR (fast freezing rate), 0.45°C/min; SFR (slow freezing rate), 0.06°C/min; UFR (ultra-fast freezing rate), 1.20°C/min. Thawing methods: RFT, refrigerator at 2°C; UTC, cooking from frozen state; WAT, water immersion at 25°C.

[a,b]Means with different lowercase letters differ significantly ($P < 0.05$).

[1]Standard error of the means.

drips and moisture on the measuring surface can cause higher lightness (Nocito et al., 1973; Owens et al., 2000). However, although significant, the numerical difference in L^* values is very small (less than 1.5 units), and it would be less likely to result in any practical differences to consumers in lightness.

Texture profile analysis

Significant main effects (freezing rate and thawing methods) on hardness and their interaction effect on cohesiveness were found (Figure 2), but no impacts on other texture profile characteristics, such as springiness, gumminess, and adhesiveness, were found ($P > 0.05$). Freezing rate affected the hardness of cooked patties, wherein the UFR patties had the lowest hardness values, followed by FFR and SFR ($P < 0.05$). Thawing methods also affected the hardness values, wherein WAT had significantly lower hardness than UTC and RFT ($P < 0.05$), but no difference between UTC and RFT was found ($P > 0.05$). In terms of cohesiveness, there was a significant interaction between freezing rate and thawing method, wherein UTC had higher cohesiveness values than WAT when SFR was applied first ($P < 0.05$). However, when patties were assigned to either FFR or UFR, there was no difference between UTC and WAT ($P > 0.05$). This observation could indicate that cohesiveness may only be affected by thawing methods when SFR is applied to patties.

Tuell et al. (2020) reported that increasing the initial freezing rate of subprimals prior to further processing resulted in a decrease in the freeze-thaw–related quality deterioration of pork patties. Other studies have also determined that subjecting meat products to 1 to 2 repeated freezing-thawing cycles results in increased hardness. This is attributed to structural damage to muscle cells, particularly the significant denaturation of myofibrillar and sarcoplasmic proteins (Kim et al., 2016; Tuell et al., 2020). Although this is very limited information regarding impacts of thawing methods on meat quality attributes, it could lead to a change in protein carbonylation (Xia et al., 2012). Such changes may result in decreases in important properties, such as WHC and gel strength, which are closely related to protein functionality (Xia et al., 2012).

In the current study, there are limitations for us to interpret the texture profile results and draw meaningful conclusions about technological properties of frozen/thawed meat patties under the given conditions without sensory data. A significant difference was observed in UTC patties assigned to SFR, wherein the patties had higher cohesiveness values compared with WAT patties. However, it is uncertain whether the observed difference in cohesiveness values would translate into affecting the sensory attributes. Further research determining the combined impact of freezing/thawing conditions on eating quality characteristics would be beneficial. Nevertheless, it is of interest to note that, in general, there was no difference between UTC (direct cooking without thawing) patties and other frozen/thawed-then-cooked patties (RFT and WAT) in most texture profile attributes, indicating that direct cooking of frozen patties (without additional thawing process) would result in no detrimental impacts on texture profile characteristics.

Thiobarbituric acid reactive substance

Freezing rate had no impact on TBARS ($P > 0.05$, Figure 3). The relationship between freezing rate and lipid oxidation has not been fully determined. Kim et al. (2018) reported that the freezing rate did not affect the TBARS value of aged/frozen/thawed pork loin, and Wanous et al. (1989) indicated TBARS was not affected by the freezing rate. In contrast, Kim et al. (2017) suggested that fast freezing could inhibit lipid oxidation in frozen/thawed chicken breast. In terms of thawing, in the present study, there was a significant

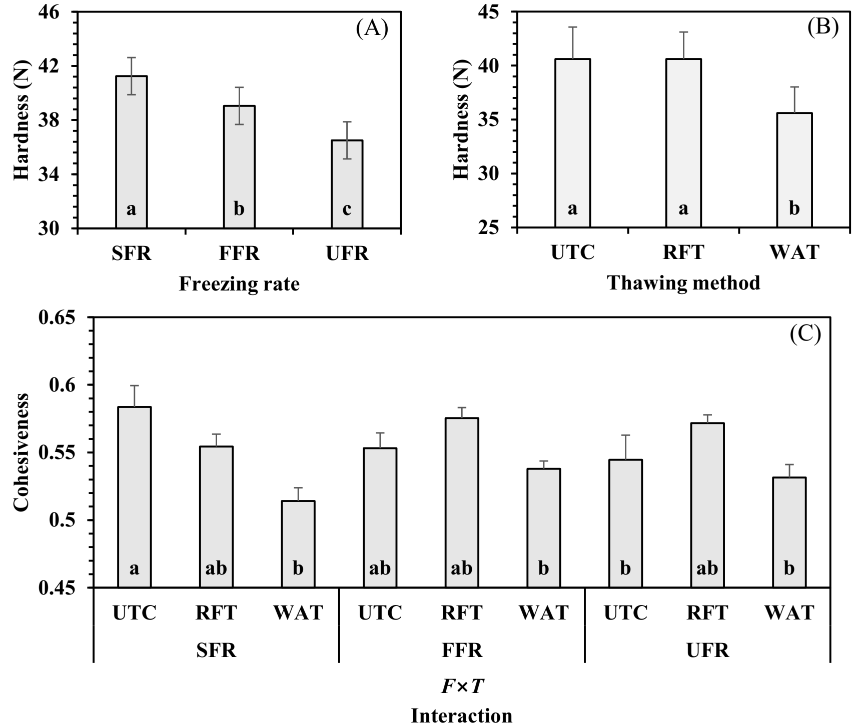

Figure 2. Textural characteristics of cooked pork patties treated by different freezing rates and thawing methods. (A) Freezing rate: FFR (fast freezing rate), 0.45°C/min; SFR (slow freezing rate), 0.06°C/min; UFR (ultra-fast freezing rate), 1.20°C/min. (B) Thawing method effect: RFT, refrigerator at 2°C; UTC, cooking from frozen state; WAT, water immersion at 25°C. (C) Interaction between freezing rate and thawing method. [a,b]Means with different lowercase letters differ significantly ($P < 0.05$).

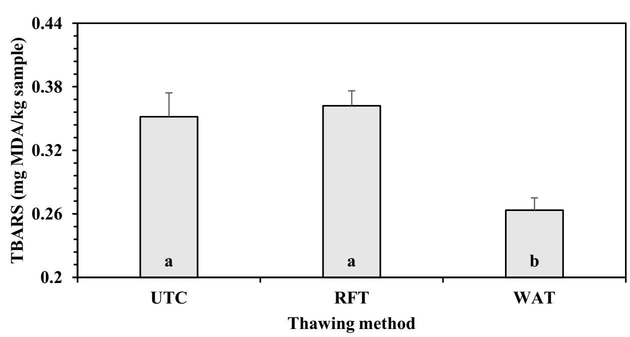

Figure 3. Thiobarbituric acid reactive substance (TBARS) of cooked patties depends on thawing methods. RFT, refrigerator at 2°C; UTC, frozen state cooking; WAT, water immersion thawing at 25°C. [a,b]Means with different lowercase letters differ significantly ($P < 0.05$).

thawing impact in which WAT had the lowest TBARS value (0.263 mg MDA/kg meat, $P < 0.05$) compared with UTC and RFT (0.352 and 0.362 mg MDA/kg meat, respectively).

In general, a level of lipid oxidation of frozen/thawed meat is higher than fresh meat (Rahman et al., 2014). The increase in lipid oxidation after a freezing and thawing cycle could be caused by the release of oxidative enzymes and pro-oxidants from disruption of cells damaged by the formation of ice crystals (Kim et al., 2018). Thus, the level of lipid oxidation of frozen/thawed meat could depend on freezing and/or thawing methods. Xia et al. (2012) found that refrigeration and immersion thawing were more effective than microwave or ambient temperature thawing in reducing lipid oxidation in frozen/thawed meat. The lower TBARS value of WAT might be explained by having less thawing time than RFT (10 vs. 970 min, respectively) and less cooking time than UTC (8.69 vs. 10.85 min, respectively). However, because the observed difference in TBARS is only about 0.1 mg MDA/kg sample between thawing methods, the practical impact that is due to the given result would likely be less meaningful.

Conclusion

The results of the current study indicate that freezing rate could have more predominant impacts on the quality characteristics of cooked pork patties, in which fast freezing improved moisture contents and minimized freezing/thawing-induced water loss of cooked patties. Although thawing conditions have some minor impacts, no major interactive effects between the freezing rate and the thawing method were found. Our study also found no differences in cooking loss and most texture profile attributes between patties with direct cooking and other frozen/thawed-then-cooked patties, indicating direct cooking of frozen patties (without additional thawing process) would result in no detrimental impacts on meat quality characteristics. This may indicate that a defrosting process prior to cooking frozen pork patties may not be necessary. Our results suggest that fast freezing can improve the overall quality of cooked patties, whereas combined impacts with thawing would be practically less meaningful. Consumers who purchase frozen patties may suggest that there may be no notable negative changes in the quality characteristics of cooked patties, even if they choose and use an easy thawing (or direct cooking without thawing) method. These findings can provide practical implications for the meat industry and consumers alike.

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