The impact of high pressure processing and pulsed electric field processing on physicochemical and sensory characteristics of lamb meat

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2019

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A thesis submitted to

Auckland University of Technology

in partial fulfillment of the requirements for the degree

of Doctor of Philosophy (PhD)

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Abstract

To better understand attitude of Chinese consumers towards lamb meat, perception and purchasing behavior of Chinese consumers for red meat were investigated. Chinese consumers placed importance on nutritional and health benefits of red meat like beef and lamb than high cholesterol of red meat like pork. It was also found that freshness was the most important factor affecting purchase intention. Most Chinese consumers purchased imported meat due to the safety concerns and the perceived high-quality attributes of imported meat. Safe food and organic labels were also important. Chinese consumers perceived red meat and meat products originating from New Zealand to be of high standard in terms of safety. In terms of purchasing intention, almost 60 % of consumers consumed offal, which provides an opportunity to the New Zealand meat industry to potentially export these by-products. Tenderness, freshness, colour and off-flavour attributes of sheep meat influenced consumer purchasing intention. Interestingly, consumption of lamb meat is seasonal, and was mainly consumed in winter and spring, in accordance to the philosophy of Chinese traditional medicine. Hot pot was the most favoured cooking method when consuming lamb meat, followed by stewing, pan-fried and barbecue methods. The Chinese consumers also did not value prime cuts like the loins and legs.

The effects of HPP on the physicochemical properties and sensory characteristics of lamb meat cuts were investigated. Three lamb cuts (shank, loin and shoulder) were treated at 200 (14°C), 300 (21°C), 400 (28°C), and 600 (42°C) MPa. The results showed that lamb meat discoloration occurred when HPP was applied at high pressure levels (400MPa and 600MPa). TBARS value significantly increased as pressure increased from 200 MPa in loin cut, and 300 MPa with shoulder and shank cuts, compared to control. SFA and PUFA content significantly decreased in shank and shoulder cuts after HPP

treatment at 200 MPa compared to control, whereas SFA and PUFA content significantly decreased in loin cut after HPP treatment at 300 MPa. Free amino acids content significantly increased in shank and loin cuts with pressure increase after 200 MPa, and in shoulder cuts after 400 MPa. Temporal dominance of sensations (TDS) results showed that HPP processing affected the temporal flavour profiles. Samples treated with HPP at high pressure levels (400 and 600 MPa) were associated with browned, livery and oxidized flavour. Results in the present study highlight the possibility of applying HPP processing to lamb meat. However factors like pressure levels applied and type of cuts used during processing are important considerations as they influence physicochemical and sensory properties of lamb samples.

To gain better understanding on the effects of chilling and freezing prior to pulsed electric field processing (PEF) on volatile profile and sensory attributes of different cooked lamb muscles (i.e. shoulder, rib and loin) were investigated. Lamb samples were treated at electric field strength of 1–1.4 kV·cm−1, specific energy of 88– 109 kJ·kg−1, frequency of 90 Hz, pulse width of 20 μs and pulse number of 964. The results showed that prolonged storage time and frozen–thawed pre-treatment led to significant increases in volatile compounds due to lipid and protein oxidation. PEF also resulted in significant changes of volatile compounds in different meat cuts. Temporal dominance of sensations (TDS) showed that both storage and PEF treatment affected the temporal flavor of meaty and oxidized flavor attributes. Particularly, longer storage period was associated with oxidized flavor, while PEF treated samples were associated with browned, juicy, livery, and meaty flavour attributes.

The effects of pulse electric field (PEF) processing combined with frozen storage on physicochemical properties and sensory characteristics of different lamb meat cuts were investigated. Seven lamb cuts (knuckle, rump, topside, shoulder shank, loin and rib) were treated at electric field strength of 1-1.4 $kV.cm^{-1}$, specific energy of 88-109 $kJ.kg^{-1}$, frequency of 90

Hz, pulse width of 20 µs and pulse number of 964. PEF processing and storage affected color stability that resulted from lipid oxidation and higher temperature generated from PEF processing. Chilled rump and shank cuts had less cooking loss after PEF processing and less PEF effects on cooking loss when applied on frozen-thawed meat. PEF treatments in combination with storage had significant effects on different chilled cuts. PEF treatments significantly affected the fatty acid profiles of all frozen-thawed cut compared to storage effects. PEF treatments significantly influenced free amino acid profiles of chilled rump, loin and rib cuts compared to storage effects. However, PEF treatments had less significant effects on the free amino acid profiles of frozen lamb meat cuts compared to storage that might be due to the higher electrical conductivities induced by freezing and thawing of meat, which results in inefficient field strength being applied to the meat that decreases proteolysis. Temporal dominance of sensations (TDS) results showed that both storage and PEF treatments affected the temporal flavor profiles of meaty and oxidized flavor attributes. A longer storage period was associated with oxidized flavor, while PEF treatment for all lamb cuts were associated with browned, juicy, livery, and meaty flavor attributes. PEF processing contributed to more oxidized flavor in PEF treated frozen–thawed rib cut stored for 7 days. These results imply that both application of PEF conditions and sample pre-treatment (chilled or frozen-thawed) should be considered when determining the effect of PEF processing on meat flavor in all seven lamb cuts.

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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Qianli Ma

Ethics Approval

12 November 2013

Nazimah Hamid

Faculty of Health and Environmental Sciences

Dear Nazimah

Re Ethics Application: 13/317 Descriptive sensory analysis and consumer testing of cooked lamb meat.

Thank you for providing evidence as requested, which satisfies the points raised by the AUT University Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 12 November 2016.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 12 November 2016;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 12 November 2016 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor

Co-Authored Works & Authors Contributions

Section 4.4: Effect of chilled and freezing pre-treatments prior to pulsed electric field processing on volatile profile and sensory attributes of cooked lamb meats

Journal: Innovative Food Science & Emerging Technologies

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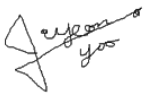

Michelle Yoo

Kevin Kantono

Farnaz Faridnia

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisors Prof. *Nazimah Hamid* and Prof. *Indrawati Oey* for the continuous support of my Ph.D study and related research, for her patience, motivation, and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study. I would also like to thank our School Manager Brid Lorigan, thank you for your continuous support for the project. In addition, the Postgraduate Office for the clear communication and assistance throughout my PhD journey.

Special thanks also to all my graduate friends, especially Dr.*Kevin Kantono*, *Pooja Pal* and *Frank* for sharing the literature and invaluable assistance.

I would also like to convey thanks to people in Chemistry and Microbiology technician teams who helped and encouraged me during this year and the Faculty for providing the laboratory facilities.

Last but not the least, I would like to thank my family: my wife and supporting me spiritually throughout writing this thesis and my life in general.

Thank you very much, everyone!

Qianli Ma

Chapter 1. Introduction

1.1. Background of the research

New Zealand is the one of world's largest exporters of lamb, making sheep farming one of its most important agricultural industries (Lin et al., 1988). Lamb is rich in conjugated linoleic acid and relatively low in fat and cholesterol. According to Beef & Lamb (2018), China imported the largest amount of New Zealand lamb (approximately 118,000 tonnes) between 2016 to 2017. Nowadays, with improved income, Chinese consumers consider imported products as being high quality. Since 1990s, the number of overseas supermarkets have been on an increase in China, playing a more important role than domestic supermarkets according to Goldman (2000). These supermarkets offer convenience to Chinese consumers to purchase imported meat and their products. However, the high cost of importing these products is the main reason affecting product purchase. Price is the main factor affecting consumption of lamb compared to the nutritional value and taste of lamb (Schroeder, Jerrick, Jones, & Spaeth, 2001).

Consumers like meat and their products to be fresh, juicy, flavourful, tender and nutritious (Dransfield, 2001, 2003; Ngapo & Dransfield, 2006). Lean, palatable and nutritional attributes drive purchase and "willingness to pay" decisions of consumers (Pethick, Banks, Hales, & Ross, 2006). Overall liking, tenderness, flavour and cooking odour are considered main factors by consumers, which contribute to eating qualities of sheep meat (Pethick, Hopkins, D'Souza, Thompson, & Walker, 2005; Pleasants, Thompson, & Pethick, 2005). Meat tenderness is the primary factor that influences the acceptability and eating quality of meat. Tenderness is determined by species, age, fat content, gender, retail cut chosen, method of cooking, and muscle type (Dransfield, 2001). Sanudo et al (2000) reported that consumers preferred less visible fat when buying specific cuts of meat and will remove excessive fat before cooking or when eating a meal.

With developing economy and improved lifestyle, there is a growing concern about food security by Chinese consumers (Chan et al., 2006). Min & Ahn (2005) reported that there were significant changes in Chinese consumers' conceptual consumption and criterions on food quality. Consumers preferred safe, nutritious and quality food. These factors are considered important in influencing consumers' choice of foods (Verbeke et al., 2010). The younger generation meat consumer have more knowledge on health, and are aware about fat content and saturated fatty acids content in food (Sanudo et al., 2000). Bernués, Ripoll, & Panea (2012) investigated consumer attitudes towards lamb quality in terms of convenience aspects and opinions. The research showed that patterns in consumption and buying attitude of meat are affected by socio-economic status and culture practices. The consumption of food products in general varies significantly with marital status, age, education, household size and income, ethnic background, religion, and occupation (Muca, Thoma, Kapaj, & Guri, 2013). Feldmann & Hamm (2015) also reported that location of residence, yearly income, and education level are the main factors that influence consumer buying attitude. Brunsø, Scholderer, & Grunert (2004) established that a food-related lifestyle (FRL) framework acted as a mediator between personal values and consumer behaviour. Hoffman, Muller, Schutte, Calitz, & Crafford (2005) carried out a survey to investigate the expectations, perceptions and purchasing behaviour of consumers of game meat. They explained that texture significantly influenced consumer perception of lamb meat in South Africa and Australia. Further research showed that European consumers were concerned about safety, nutrition and health, and convenience factors when purchasing meat (Bernués, Olaizola, & Corcoran, 2003). However, there is a limited research about consumption and consumer perceptions of lamb in the Chinese market.

Lipid oxidation involves a number of biochemical reactions that may influence the type and amount of chemical constituents in food (Akoh & Min, 2008). Some products of oxidation can change flavor and nutritional

quality of foods, and may liberate toxic compounds (Medina-Meza, Barnaba, & Barbosa-Cánovas, 2014). Flavor and tenderness are the most appreciated characteristics in lamb meat by consumers (Alfonso, 2000). While tenderness is probably the most important factor that determines acceptability in other species, such as beef (Boleman et al., 1997), flavor is the most important for lamb meat (Crouse, 1983), followed by tenderness. Indeed, one of the main reasons why some consumers reject lamb meat is because of its characteristic flavor (Martínez-Cerezo, Sañudo, Panea, & Olleta, 2005). On the other hand, lamb is perceived tastier than meat from other species due to the unique flavor of lamb (Alfonso, 2000).

According to Calkins & Hodgen (2007), factors that can influence meat flavor include animal species, breed, gender, age, food, and type of processing. Meats that are raw have little or no smell with a bloody flavour. Flavor is generated through thermal reactions and heating (Huang & Ho, 2001). During cooking, a number of complex thermal reactions results in the generation of flavors characteristic of meat (Mottram, 1998). More than 1000 of the volatile compounds include ketones, aldehydes, alcohols, and nitrogen or sulphur containing compounds, are reported in beef, pork, mutton, and chicken (Mottram, 1998). A high number of volatiles are also produced, including acids, aldehydes and ketones, which may react with metabolites of the Maillard reaction and thiamine, to form flavour-active end-products, such as nitrogen and sulphur compounds (Mottram, 1998). According to Madruga (1997), the aroma and taste of the meat are directly associated with the fat content in the muscle. Lipid-derived volatile compounds responsible for rancid off-flavours can develop when the oxidation level of meat is very high or when the oxidation reactions are produced before or after cooking (Mottram, 1998). Fu & Ho (1997) and Priolo, Micol, & Agabriel (2001) concluded that the generation of volatile compounds can be affected by various muscles or cuts of meat, sample preparation or collection, and processing methods. Biochemical reactions that occur during aging of meat may result in enzymatic oxidation of

unsaturated fatty acids, and can cause proteins, peptides and amino acids to further interact, further generating volatile compounds (Huang & Ho, 2001).

Free amino acids (FAA) are important precursors of flavour compounds in meats and other foods, that can influence cooked meat palatability (Baryłko-Pikielna & Kostyra, 2007; Chiang, Yen, & Mau, 2007). Free amino acids contribute to meat taste by being substrates in chemical reactions that form volatile compounds upon cooking (Janes, Bolta, Skrlep, & Prevolnik, 2012). For instance, tryptophan, alanine, tyrosine, glycine, histidine, leucine and phenylalanine are associated with sweet taste; valine, tyrosine, isoleucine, phenylalanine, tryptophan and leucine, are associated with bitter taste; aspartic and glutamic acid, histidine, asparagine, succinate and lactate with sour taste; glutamic and aspartic acid with salty flavour; and glutamate, aspartate, carnosine and inosine monophosphate (IMP) with savoury/beefy taste (umami taste) (Toshihide Nishimura & Kato, 1988). Furthermore, certain FAA (e.g., glutamate, glycine, and β-alanine) contribute to "meaty flavour" (San Gabriel & Uneyama, 2013). Martín, Antequera, Ventanas, Benítez-Donoso, & Córdoba (2001) reported that free amino acids content have been highly associated with the taste and flavour of ham. During cooking, FAA react with sugars and possibly lipid oxidation products to produce heterocyclic compounds that are responsible for the flavor of cooked foods (Mottram, 1998). Proteolysis can greatly influence the quality characteristics of meat during processing (such as aging and dry-curing), as it is an important source of flavour compounds (FAA and small peptides).

Several studies have reported changes in amino acid composition with processing of meat. Ohmori, Taji, Shigehisa, Hayashi, & Rikimaru (1991) found that high-pressure treatment (100 to 300MPa for 10mins at 25 °C) modulated the proteolytic activities to increase free amino acid content and can improve beef quality. The content of total FAA significantly increased due to the protein hydrolysis during processing of Chinese traditional dry-cured bacon (Laròu) production (Zhang & Zhao, 2016). In addition, changes in the content of FAA are used for measuring proteolytic activity throughout

the ripening processing of dry-cured ham (Pérez-Palacios, Ruiz, Barat, Aristoy, & Antequera, 2010). At the final processing stage, proline, tyrosine, leucine, phenylalanine and tryptophan were present at higher levels in pre-cured frozen ham compared to refrigerated hams. On the other hand, glutamine and ornithine were present in higher levels in refrigerated frozen hams than pre-cured hams. Rabie, Peres, & Malcata (2014) reported significant changes in amino acids during the aging of sausages made of different species meats (turkey, horse and beef). The concentration of total FAA in horse and beef sausages significantly increased during 28 days of chilled storage. However, it decreased for turkey sausage (Lopez-Bote et al., 1998).

Consumer demand is on the increase for products that are fresh tasting, additive-free and microbiologically safe, convenient to use, having an extended shelf-life, and requiring minimal preparation time. Raso & Barbosa-Cánovas (2003) identified that an ideal processing method should have ability to inactivate spoilage and pathogenic microorganisms, maintain sensory properties and nutritional values of products, and produce a product acceptable to consumers and regulatory agencies. Many processing methods do not meet all these criteria. Although chilling and freezing can maintain, to a certain degree, the freshness of food, microorganisms' growth is only delayed or inhibited. Thermal processing in turn, can cause inactivation of microorganisms and enzymes can contribute to safer and more stable products. However there are downside effects on the organoleptic qualities in terms of appearance, flavour, and nutritional value and taste of the final product (Wilson, Dabrowski, Stringer, Moezelaar, & Brocklehurst, 2008). The applications of high-pressure processing (HPP) and pulsed electric field technologies can be utilized to improve or maintain food quality (S Toepfl, Mathys, Heinz, & Knorr, 2006).

HPP is a natural and environmentally friendly method that can pasteurize and increase shelf life of food products (Welti-Chanes et al., 2005). Although HPP is a "mild-technology," its application in foods high in fat can increase

oxidative processes. Pressure treatments were found to induce lipid oxidation in food products like minced beef (Rivas-Cañedo, Fernández-García, & Nuñez, 2009), ham (Clariana & García-Regueiro, 2011), turkey thigh muscles (Tuboly, Lebovics, Gaál, Mészáros, & Farkas, 2003), and chicken breast muscles (Kr & Skibsted, 2004). Pulsed electric field (PEF) technology is a non-thermal processing method with low energy requirements that can minimize quality deterioration of food. PEF is an emerging food processing technology, which has been widely investigated in terms of its potential for industrial pasteurization of liquid food such as beer, fruit juice and milk (Bermúdez-Aguirre, Fernández, Esquivel, Dunne, & Barbosa-Cánovas, 2011; Milani, Alkhafaji, & Silva, 2015; Timmermans et al., 2014). Recently however, extensive studies have been conducted on muscle foods. There is a growing interest on PEF-induced modifications in the structure and texture of meat. It has been reported that the use of PEF in muscle foods (especially in beef) can enhance cell permeability due to electroporation and consequently enhance proteolysis that contributes to tenderisation (Bekhit, van de Ven, Suwandy, Fahri, & Hopkins, 2014; Jaeger, Balasa, & Knorr, 2008; Suwandy, Carne, van de Ven, Bekhit, & Hopkins, 2015b; S Toepfl, Heinz, & Knorr, 2007). Lopp & Weber (2005) reported that PEF treatment (3.5 kV·cm−1, 20 Hz, 5 s) enhanced tenderness of beef triceps brachii muscles. However, in another research (O'Dowd, Arimi, Noci, Cronin, & Lyng, 2013), PEF treatments (1.1–2.8 $kV \cdot cm^{-1}$, 5–200 Hz, 12.7–226 $kJ \cdot kg^{-1}$) did not result in instrumental texture changes in beef *semitendinosus* muscle. PEF treatment in combination with storage can increase rate of proteolysis, which contribute to increased meat tenderness (Faridnia et al., 2015). In addition, Bekhit, Hopkins, Geesink, Bekhit, & Franks (2014) concluded that PEF could potentially increase the extent of calcium ions release, further triggering liberation of calpains. As PEF processing may activate enzymes, this process can increase free amino acids contents in meat. Up to now, no research has been carried out to determine the effect of PEF and HPP processing on the physicochemical properties and sensory characteristics of lamb meat.

Several approaches have been used to investigate the eating quality attributes of meat. This include the use of surveys (Hoffman et al., 2005), consumer sensory testing (Lagerstedt, Enfält, Johansson, & Lundström, 2008), descriptive analysis (Corbin et al., 2015; Oltra et al., 2015), time-intensity (TI) analysis (Lorido, Hort, Estévez, & Ventanas, 2016) and temporal dominance of sensation (TDS) (Ma et al., 2016; Pineau et al., 2009). Conventional static sensory assessment is only carried out at a single point evaluation by panelist and it can miss information on sensory changes over time. To overcome this drawback, the Temporal Dominance of Sensations (TDS) method has been developed to study the temporal dimensions of flavor over the time of consumption. TDS panelists require some training as several attributes can be evaluated simultaneously using this method (Monaco, Miele, Volpe, Picone, & Cavella, 2014). This method has been used to study the perception of food such as fish sticks (Albert, Salvador, Schlich, & Fiszman, 2012), low-sodium Mozzarella cheese (Rodrigues, Gonçalves, Pereira, Carneiro, & Pinheiro, 2014), bread (Panouillé, Saint-Eve, Déléris, Le Bleis, & Souchon, 2014), wines (Meillon et al., 2010) and sausage (Devezeaux de Lavergne, Derks, Ketel, de Wijk, & Stieger, 2015).

1.2. Aim and Objectives

The overall objective of this research was to gain a better understanding on important lamb meat attributes that influence consumer perception and purchasing behavior, and to explore how non-thermal processing methods (like HPP and PEF) can be applied to improve lamb meat quality. The research presented in this thesis attempts to answer the following research questions:

1. To determine factors that influence perception and purchasing behavior of lamb meat by Chinese consumers (Section 4.1).

2. To determine how HPP treatment affects physicochemical and sensory qualities of three different lamb meat cuts (Section 4.2).

3. To determine how PEF treatment affects physicochemical and sensory qualities of seven different lamb meat cuts (Section 4.3 & 4.4).

4. To determine how do pre-treatments (freezing) prior to PEF affect the quality attributes of seven different lamb meat (Section 4.3 & 4.4).

Chapter 2. Literature review

2.1. New Zealand lamb meat industry

The value of exported meat significantly contributes to the New Zealand economy. Sheep meat and its products have a favourable micronutrient content, and contain wide ranging minerals and vitamins (Kouvari, Tyrovolas, & Panagiotakos, 2017). According to MIA (2016), New Zealand is the largest exporter of sheep meat in the world with an export earning of NZ $ 2.8 billion for the year that ended in September 2016 (Table 1).

Table 1 Top seven countries exports New Zealand sheep meat at 12 months ended 30 September 2016 (Beef & Lamb, 2018)

	Percentage of total sheep meat export volume	Volume (tonnes)	Value (NZ$ m)
China	36%	139690	569.3
UK	17%	67224	533.2
USA	6%	22268	272.8
Germany	5%	19842	262.8
Netherlands	5%	18083	230.7
France	3%	11893	118.6
Canada	3%	10096	81.7
Total	100%	386084	2776.6

Sheep meat is widely consumed for nutritional and sensorial reasons, rather than traditional and religious reasons (Kegalj, Krvavica, Vrdoljak, Ljubičić, & Dragaš, 2011). Meat quality is important when establishing and maintaining export markets for meat (Troy & Kerry, 2010). Compared with other markets, for example, Europe, exports of sheep meat to most countries in Asia are relatively low (Figure 1). Exports of New Zealand sheep meat to the whole north Asian region (comprising Japan, Korea, China, and Taiwan) represented less than 10% (on a weight basis) of what was exported to the European Union (MIA, 2016).

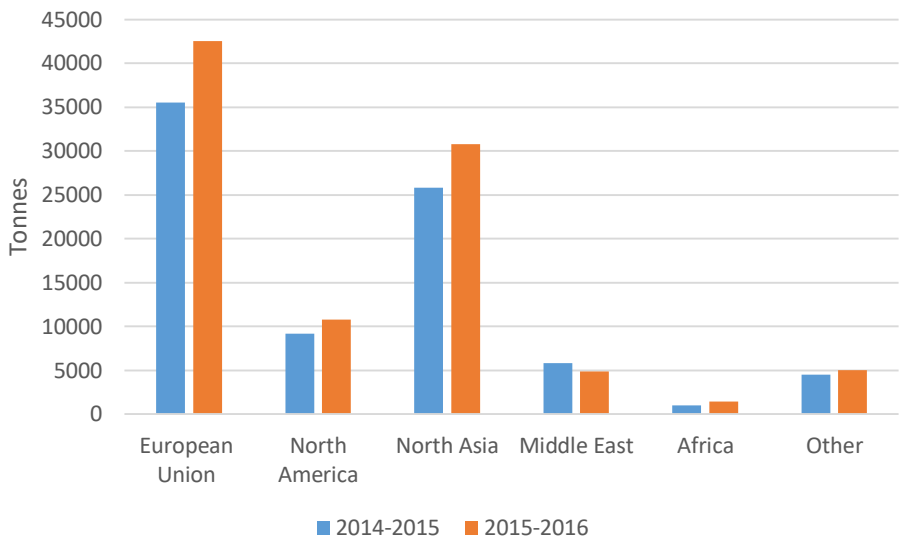

Figure 1 New Zealand sheep export data (Beef & Lamb, 2018)

New Zealand lamb is exported as a frozen product. With improved hygienic processing, packaging and chilling technologies, New Zealand meat processors have been allowed to supply chilled unfrozen lamb cuts to overseas markets (Y. H. B. Kim, Frandsen, & Rosenvold, 2011). Presently, the UK is top country where sheep meat is exported, both in terms of volume and value, especially for chilled meat (Table 2). Compared to frozen meat, chilled meat is from the higher value portions of the carcass, and are perceived as being more tender and juicy (Rosenvold & Wiklund, 2011). Furthermore, chilled prime cuts are considered a higher quality product with higher prices, due to the improved tenderness by the aging processes (Resconi et al., 2010). However, frozen sheep meat remains to be a big demand in a market, like China (Table 2). Freezing provides the advantage of longer shelf life without large changes in the properties of fresh meat (Muela, Monge, Sañudo, Campo, & Beltrán, 2016).

Table 2 Chilled and frozen sheep export data from Beef & Lamb (2018)

	Region	Percentage of total sheep meat export volume	Volume (tonnes)	Value (NZ$m)
Chilled sheep meat	UK	41%	28823	297.3
	USA	10%	6872	102.1
	Jordan	8%	5842	34.9
	France	8%	5767	64.5
	Netherlands	8%	5389	80.4
	Germany	7%	5154	87.8
	Japan	4%	2690	34.3
	Total	100%	70855	844.5
Frozen sheep meat	China	44%	139690	569.3
	UK	12%	38401	235.9
	USA	5%	15396	170.8
	Germany	5%	14688	175
	Netherlands	4%	12694	150.3
	Taiwan	3%	9326	47.2
	Malaysia	3%	8755	42.3
	Total	100%	315229	1932.1

In the past two decades, the growth in exporting chilled meat with primal or sub-primal cuts has become slow but constant (McDermott, Saunders, Zellman, Hope, & Fisher, 2008). Extending low-value cuts and diversifying into value-added and chilled products, can improve the quality of exported meat. There are five primal (primary) cuts (full leg, flap, mid-loin, rib-loin, and forequarter) that are divided according to muscle distribution. Lamb can vary in appearance and consumer eating qualities like colour, flavour, texture, and juiciness. It is well established that this difference is attributable to the combined effects of antemortem factors such as sex, breed, age and feeding background (Berge et al., 2003). However, in the same animal, different cuts vary in colour, flavour, texture, and juiciness.

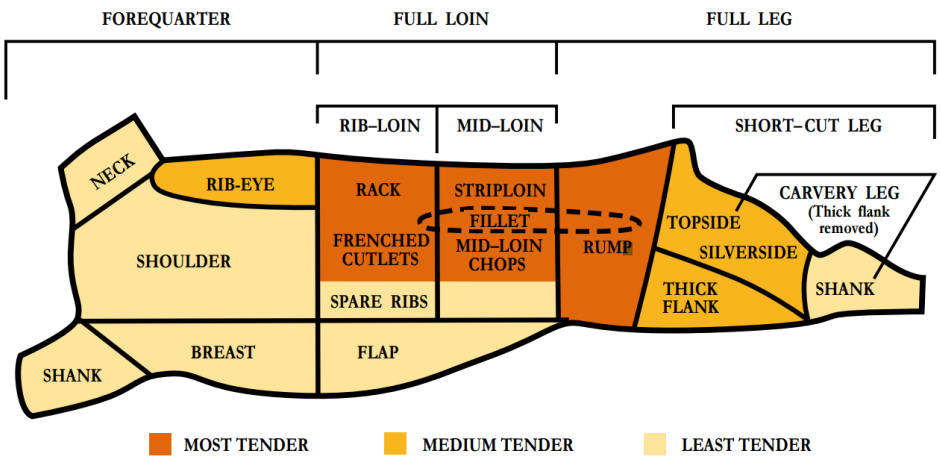

Figure 2 Diagram of lamb meat cut (Beef & Lamb, 2018)

When cutting meat, cuts are separated into tender and less tender cuts, and lean and fatty cuts (Figure 2). In recent decades, demand for the more tender middle cuts such as loin and rib has increased, while demand for the tougher end cuts, such as chuck and round, have decreased (Jung, Hwang, & Joo, 2016). Improvements in the prediction of primal and retail cut yields are needed to drive process optimization (Ngo et al., 2016). Many studies have reported that consumers are willing to pay for a high quality, tender cut (Kukowski, Maddock, Wulf, Fausti, & Taylor, 2005; Lusk, Fox, Schroeder, Mintert, & Koohmaraie, 2001). Less exercised skeletal muscles that provide support, like cuts of meat along the backbone (e.g. loin), are usually more tender than skeletal muscles used in locomotion (Vaclavik & Christian, 2008). As a result, the meat industry has focused on marketing the middle cuts which are tender, juicy, and flavourful products (Lepper-Blilie, Berg, Germolus, Buchanan, & Berg, 2014). Consumers' demand for middle cuts has led to the lower utilization of the end cuts. Consequently, chuck and round cuts have been sold at a lower price and used mainly for roasts (Jung et al., 2016).

2.2. Consumer perception and purchase behaviours of meat

As consumers are the final target for the meat production chain, their expectations of meat and meat products directly impact on profitability of the meat industry. Therefore, it is important to have a good understanding of consumer perception and purchase intentions of meat and its products to improve profitability of the meat industry.

Consumer perception is how customers usually view or feel about certain services and product. Purchase intentions are willingness of a person to give preference to products having desirable features over other products, in their purchase considerations. Consumer purchase intentions also play an important role in marketing strategies because they permit companies to evaluate how many products can be produced according to the demand (Kabir & Jahan, 2014). Consumer perception can be affected by consumers' experience with themselves. The physiological characteristics of meat and its products, as well as how they are produced, handled and distributed can affect consumer perception (Claret et al., 2014). The physical properties of the meat (colour, visible fat and tenderness) contribute to the consumers "expected quality" (Troy & Kerry, 2010). For example, meat expected quality decreases when visible fat is present in meat (Steenkamp & Van Trijp, 1996). "Quality" and "healthfulness" are the most important features influencing consumers' choice for foods. With regards to the Total Food Quality Model, quality cues revolve around the ability of the consumers to evaluate food quality (such as costs, extrinsic and intrinsic quality cues) before and after purchase (Grunert, Larsen, Madsen, & Baadsgaard, 1996). Another model proposed by Peri (2006) to understand the relationship between the food product (safety, sensory, ethical, and nutrition) and product trading (price, certification, and traceability). Consumers' choices can be affected by their knowledge of diet and their attitudes to meat products, especially preference of consumption of specific meat types (Guenther, Jensen, Batres-Marquez, & Chen, 2005). Nowadays, consumer prefer food that is safe, nutritious and high quality (Verbeke et al., 2010). After a series of food safety

events happening in Greece, meat consumers have started to be concern about meat origin, food safety, and food production process (Krystallis & Arvanitoyannis, 2006). Moreover, Van Wezemael, Verbeke, de Barcellos, Scholderer, & Perez-Cueto (2010) showed that European beef consumers preferred fresh beef compared to processed beef as freshness is an indicator of meat healthfulness.

Sensory characteristics of meat that also affects consumer perception and purchase intentions, are related to several factors, such as the appearance of meat, and in-mouth perception (texture and flavour). These traits depend on many factors such as genotype (Duckett & Kuber, 2001), age (Pethick et al., 2005), sex, aging, and storage conditions (Channon, Kerr, & Walker, 2004). Banović, Grunert, Barreira, & Aguiar Fontes (2009) and Verbeke et al (2005) concluded that appearance characteristics like color, visible fat and degree of marbling determine consumers' expectations of meat quality. Color has been considered as the most important fresh meat characteristics influencing consumer purchase (Gracia & de Magistris, 2013; Ngapo, Martin, & Dransfield, 2007; Verbeke et al., 2005). Bernués, Ripoll, & Panea (2012) reported that Spanish consumers preferred lighter colored lamb that they were used to, and in other countries consumers preferred darker lamb due to consumption habits. Fat content is another appearance characteristic that is related to consumer purchase behaviour. Raes, De Smet, & Demeyer (2004) concluded that factors like species and muscle types, gender and age, as well as diet and genotype, influenced the quantity and the quality of fat. Eating quality attributes like tenderness and juiciness, positively influence preferences of consumers for pork (Aaslyng et al., 2007), beef (Bello Acebrón & Calvo Dopico, 2000; Polkinghorne & Thompson, 2010) and lamb (Font i Furnols et al., 2009). Furthermore, Maria Font-i-Furnols & Luis Guerrero, (2014) stated that tenderness, juiciness and taste of meat were highly associated with purchase intention. Flavour and taste enjoyment are also highly correlated with consumption satisfaction of pork and its products c (O'Quinn et al., 2012, Resano, Pérez-Cueto, de Barcellos, et al., 2011). Lamb

has a special flavour compared to beef and pork. Consumers found lamb with stronger flavour to be less palatable (Rhee & Ziprin, 1996). Lambs that graze on pasture and older lambs can have an intense mutton odor and flavor, due to its higher content of α-linolenic acid and oxidation products, which can make it unacceptable to consumers (Díaz et al., 2005; Font i Furnols et al., 2006, 2009). In addition, cooking methods also affected consumer preferences. For example, consumers preferred fried flavour of pork than boiled flavors (Aaslyng et al., 2007).

With the development of technology, more and more marketing strategies such as online shops, call centres, or direct selling have been employed to increase market sales (Verbeke & Ward, 2006). Price is important in motivating consumer's intention to purchase, and is influenced by demographic characteristics (Kotler & Keller, 2006; Reicks et al., 2011). Du Plessis & du Rand (2012) reported that price was the main reason for purchasing lamb meat, followed by safety, traceability, quality, and country of origin. Lamb and beef origin and system of feeding are the most important factors affecting purchase intention rather than price (Font I Furnols et al., 2011). The origin of meat and meat products with certification also affect consumer preference. For example, consumers prefer to buy meat with food safety label authorized by the government than local butchers without labels (Imami, Chan-Halbrendt, Zhang, & Zhllima, 2011). Consumers were reported to prefer domestic lamb in Norway, Italy and Albania due to local products being considered as fresh, tasty and high quality (Hersleth, Næs, Rødbotten, Lind, & Monteleone, 2012; Imami et al., 2011, Chambers, Lobb, Butler, Harvey, & Traill, 2007). Furthermore, consumers strongly preferred organic production of meat because of its safety, nutrition wholesomeness, as well as management and environmental aspects (Fernqvist & Ekelund, 2014), and were willing to pay more for certified organic products (Kim, Suwunnamek, & Toyoda, 2008).

New Zealand's second largest market for beef and sheep exports is China with exports of frozen sheep and beef meat worth about NZ $1 billion in the

year to December 2016. This is a trade that has grown five-fold since 2011. Population in China has dramatically increased and the country achieved remarkable economic growth over the past decade, making China an important role player in the international economy. As income increased, many related social changes affecting lifestyles, dietary habits, and consumer behavior have taken place (Huang & Yang, 2009). Mao, Hopkins, Zhang, & Luo (2016) reported that significant differences in meat consumption exist between different regions, urban and rural consumers, and even between different seasons, due to income level, education, meat availability, and tradition. With increased demand for lamb, local meat producers are unable to meet the needs of their consumers, thereby creating both export opportunities and an increased consumption of imported lamb. Since the melamine-contaminated milk scandal happened in 2008, food safety incidents in China have received considerable attention (Knight, Gao, Garrett, & Deans, 2008). Hence many Chinese consumers prefer to buy imported rather than locally produced meat due to safety, quality, and health factors (Henchion, McCarthy, Resconi, & Troy, 2014). Therefore, it is important for the New Zealand meat industry to understand Chinese consumer perception and purchase behaviours of lamb meat.

2.3. Meat characteristics of lamb

Meat is important in maintaining a healthy and balanced diet due to its nutritional composition. High grade meat is rich in proteins, essential amino acids and polyunsaturated fatty acids (PUFA). In meat, nutritional composition is influenced by species, genotypes, nutritional and environmental factors, slaughtering and processing conditions (Huff Lonergan, Zhang, & Lonergan, 2010).

2.3.1. Meat muscle

Consumers are willing to pay for red meat products of high quality and consistent tenderness (Boleman et al., 1997; Robbins et al., 2003). The skeletal muscle is a major factor affecting meat quality development (Huff

Lonergan et al., 2010). Connective tissue in the skeletal muscle contains endomysium (surrounds each muscle fiber), epimysium (surrounds the muscle as a whole), and perimysium (surrounds bundles of muscle fibers) (Astruc, 2014; Davies, 2004) (Figure 3).

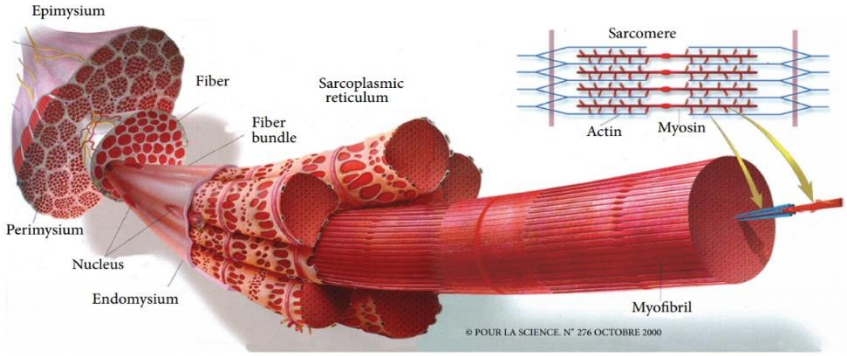

Figure 3 Schematic structure of a skeletal muscle

Myofibrils are arranged in bundles that make up nearly the whole intracellular volume of muscle fibers. Myofibrils are between 10 and 100 µm in diameter and from 1- 2 up to 300mm in length, sometimes spanning the whole muscle length. As shown in Figure 4, cylindrical organelle of myofibril is made up of sarcomeres, which contribute to the striated appearance of the muscle cell. A single sarcomere is the structure between two neighboring Z-lines. The region of I-bands surrounds the Z-line.

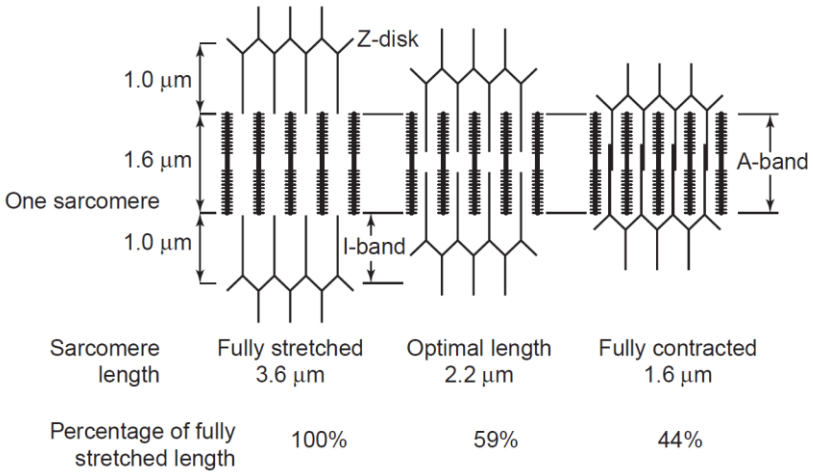

Figure 4 The sarcomere, which is the smallest contractile unit of the muscle, is delimited by the Z disks. It consists of at least thirty different proteins, of which the most abundant are myosin and actin (Davies, 2004)

Two sets of interdigitating filaments of sarcomeres, thick (protein and myosin) and thin (protein actin), contribute to the contraction of voluntary muscles (Davies, 2004). Myofilaments are mainly made up of myosin molecules that has ATPase activity catalyzing the breakdown of ATP into ADP, providing energy for contraction of muscle (Listrat et al., 2016). When contraction happens, the thick and thin filaments interact in the myosin region. Actomyosin is responsible for the interaction of myosin and actin (Figure 5).

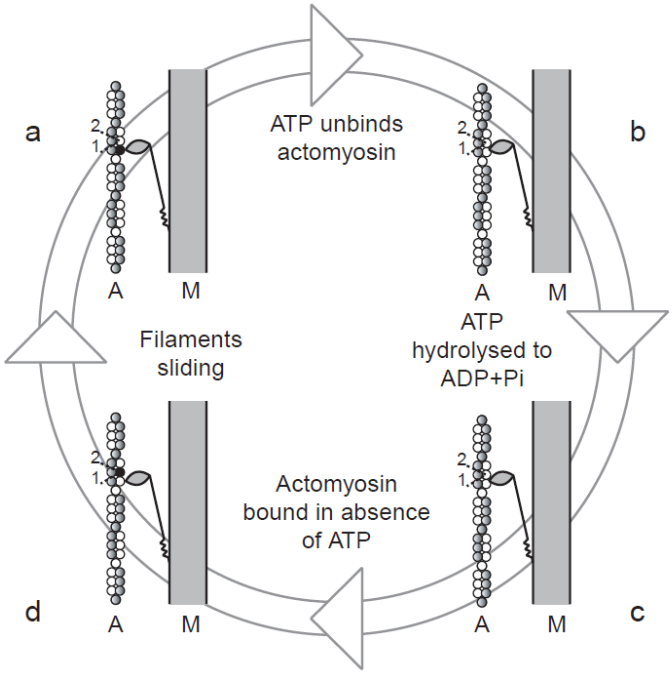

Figure 5 The actomyosin cycle. Reversible changes in myosin and actin association are due to the action of ATP and its products of hydrolysis. In the step (d) to (a), the actin filament A is 'rowed' past the thicker myosin filament M by an association of an adjacent globular actin molecule with the myosin cross-bridge (Davies, 2004).

However, when the animal dies, ATP supply depletes and actomyosin bonds become permanent. In meat, the degree of myofibrils shortening will influence meat tenderness. Sarcomeres that are very short will make meat tougher and age less efficiently (Kemp, Sensky, Bardsley, Buttery, & Parr, 2010).

2.3.2. Colour

Meat colour is a key feature that influences a consumer's buying decision, because it is an indicator of freshness and quality (Faustman & Cassens, 1990). Lamb meat discoloration is unacceptable to many consumers and can attract heavily discounted prices (Khliji, van de Ven, Lamb, Lanza, & Hopkins, 2010). Therefore, it is important to develop efficient methods for maintaining colour to satisfy consumer demand.

Water-soluble myoglobin can store oxygen for aerobic muscle metabolism, which contribute to meat colour. Colour change in meat can be attributed to either myoglobin oxygenation that turns to oxymyoglobin (red) or oxidation of myoglobin to metmyoglobin (brown) (Figure 6). Many intrinsic (muscle pH and fibre, age, species and feed type) and extrinsic (animal pre-slaughter and refrigeration of carcass) factors influence changes in color of stored meat and accumulation rate of metmyoglobin (Calnan, Jacob, Pethick, & Gardner, 2016; Jacob, D'Antuono, Gilmour, & Warner, 2014). Furthermore, the environmental factors (retail display) such as packaging storage atmosphere, oxygen content, temperature and retail sale of meat also influenced meat color (Troy & Kerry, 2010).

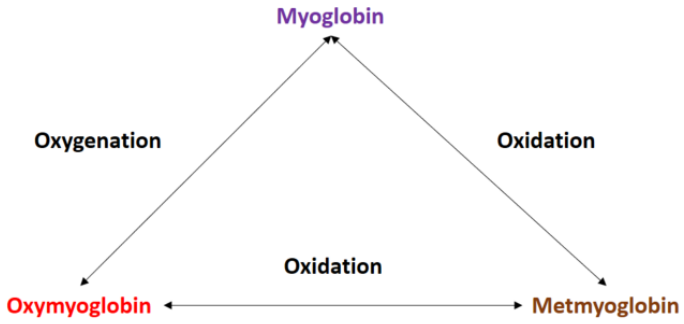

Figure 6 Interconversion of meat pigments

2.3.3. Tenderness

The tenderness of meat is influenced by the solubility of connective tissue, shortening of sarcomere shortening during rigor, proteins associated with myofibrillar, and post-mortem myofibrillar proteolysis (Koohmaraie &

Geesink, 2006). The calpain system affected proteolysis and calpain-specific inhibitor calpastatin is responsible for tenderization ((Kemp et al., 2010; Veiseth, Shackelford, Wheeler, & Koohmaraie, 2004). The proteolysis of myofibrillar and proteins contribute to the predominant changes in myofibrillar structure during post-mortem tenderization (Pearce, Rosenvold, Andersen, & Hopkins, 2011). μ- calpain and m-calpain enzymes require the presence of calpain, to remain active and works by cleaving myofibrillar proteins and weakening their structures (Pearce et al., 2011).

Muscle connective tissue is composed of collagen. The composition and structure of connective tissue affect meat tenderness (Astruc, 2014). Nishimura (2015) reported that collagen content of raw meat is highly correlated with the shear force. With cooked meat, there is a complicate relationship between shear force and collagen content depending on muscle type and cooking conditions (Dubost et al., 2013). The collagen fibers shrink and pressurize muscle fibers when meat is cooked. Collagen and muscle fibers interactions can change collagen denaturation due to heat that contribute to tenderness of cooked meat (Lepetit, 2008).

Three tenderization strategies using physical, chemical and enzymatic methods, are applied in the meat industry. The physical interventions include electrical stimulation of carcasses, freeze thaw cycles (Y. H. B. Kim, Liesse, Kemp, & Balan, 2015), pressure treatments (shock wave, ultrasound and high hydrostatic pressure) (Bolumar, Bindrich, Toepfl, Toldrá, & Heinz, 2014), aging conditions (function of temperature and time) and mechanical tenderization (blade/needle, cubing, flaking and mincing), and contraction prevention (stretching/tender stretch/alternative hanging, tender cut, wrapping, rapid crust freezing) (Weston, Rogers, & Althen, 2002). Chemical interventions include infusion, marinating or injection of the meat with calcium, sodium, and phosphate salts, as well as a commercial preparation containing maltodextrin and starch. The use of these chemical compounds normally leads to a desirable biochemical outcome that improves meat tenderness (Bekhit, Hopkins, Farouk, & Carne, 2013). Enzymatic

interventions include infusion, marinating or injection with exogenous proteases from plants, microbes and animals (Bekhit, Hopkins, et al., 2014).

2.3.4. Flavour

Flavour influences palatability of meat after appearance and tenderness. Volatiles compounds in cooked meat are derived from complex reactions induced by heat like lipid oxidation, Maillard browning, and thiamine degradation (Mottram, 1998) (Figure 7).

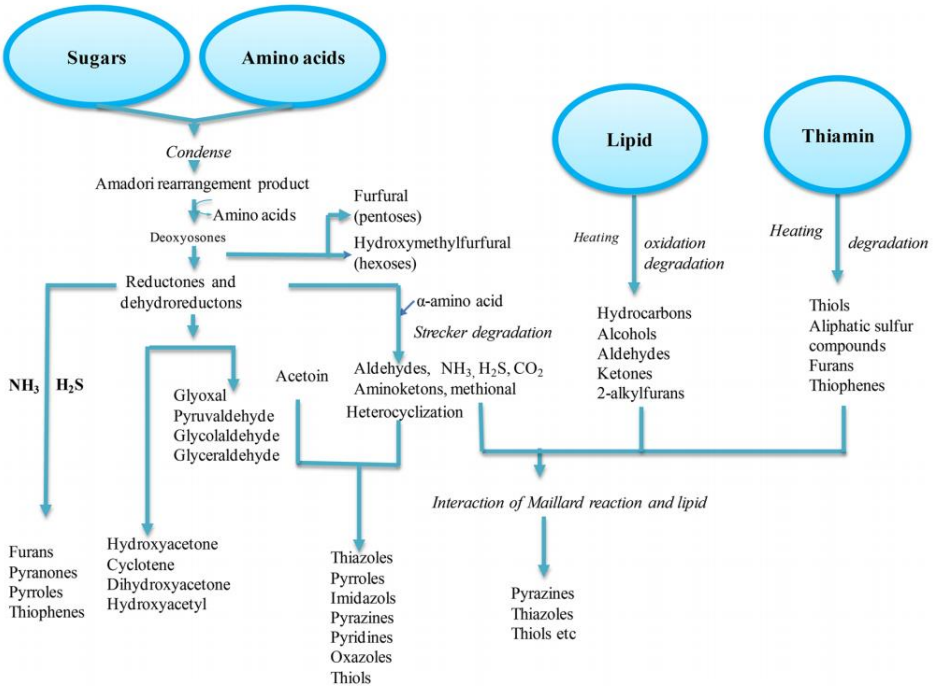

Figure 7 Schematic illustration of volatile compounds generated by Maillard reaction (Dashdorj, Amna, & Hwang, 2015)

Water-soluble components of muscles contribute meaty aroma of cooked meats. Differences in concentration and composition of lipid-derived flavours are responsible for species-specific aroma differences in cooked meats (Song et al., 2011). Maillard reaction contribute to formation of volatile compounds and influences appearance of cooked meat. (Koutsidis et al., 2008; Mottram, 1998). Two sulfur-containing amino acids, cystein and cysteine can react with sugars to form sulfur-containing flavor compounds (Elmore, Campo, Enser, & Mottram, 2002). Non-sulfur containing amino acids can react with sugars to form nitrogen-containing products like

pyrazines (Ames, Defaye, & Bates, 1997). Strecker degradation processes may occur when amino acids are degraded. For example, aldehydes (e.g., furfural) and aminoketone are final product of the Strecker degradation processes.

2.4. Non-thermal processing

For food preservation, thermal processing target and destroy microorganisms using energy. However, this might result in deleterious effects on nutritional composition and flavor of food (Alwazeer, Delbeau, Divies, & Cachon, 2003). Compared to thermal processing, non-thermal processing can maintain nutritional composition and flavors of food. Processing using high hydrostatic pressure and pulsed electric field are emerging nonthermal technologies (Barbosa-Cánovas, Góngora-Nieto, Pothakamury, & Swanson, 1999; Jaeger et al., 2008) gaining attention in recent years.

2.4.1. Why HPP and PEF processing is used for lamb meat

Meat is a rich nutrient matrix that provides a suitable environment for proliferation of meat spoilage microorganisms and common food-borne pathogens, therefore adequate preservation technologies must be applied in order to preserve its safety and quality. Meat quality is a highly subjective topic, but industry and consumers agree on a number of important quality indicators. These traits include tenderness, juiciness, appearance (colour and structure), fat and protein content, drip and cooking loss, fat quality (namely the oxidative stability of fat), and off-odours (Borggaard and Andersen 2004). Novel non-thermal technologies such as ultraviolet light (UV), ohmic heating, ultrasounds , high-pressure processing (HPP), pulsed electric field (PEF) and pulsed light treatment have the ability to inactivate microorganisms at near-ambient temperatures, avoiding thermal degradation of the food components, and consequently preserving the sensory and nutritional quality of the fresh-like food products (Pereira & Vicente, 2010).

HPP is a technology by which a product is statically treated at or above 100 MPa by means of a liquid medium. Food can be processed at ambient or even lower temperatures. Due to the isostatic transmission of pressure, the processed material experiences the pressure instantaneously with no gradient, resulting in uniform treatment irrespective of the size and geometry of the material. High-pressure modifies only noncovalent bonds and does not affect small molecules such as flavour compounds and vitamins. Therefore HPP leads to less degradation in the overall quality of processed foods in comparison to heat treated foods. As a result, HPP enables food manufacturers to respond to the growing demand for safe, fresh-looking, nutritious, and innovative food products. One important challenge associated with HPP is ensuring high levels of microbial inactivation in meat products, while maintaining those sensory characteristics that ensure their fresh appearance. The application of HPP to meat and meat products results in a modification of quality parameters such as colour, texture and water holding capacity. However there is no negative impact on the nutritional value (Bajovic et al., 2012). HPP is commercially used mainly as a non-thermal decontamination technology for processed and ready to eat (RTE) meat products with high consumer acceptance, in comparison to other non-thermal decontamination technologies such as ionizing radiation (Bajovic et al., 2012). In addition, pressure can also be applied to meat in the form of hydrodynamic pressure treatments in order to induce mechanical tissue disintegration and therefore tenderize meat. When thermal treatment is applied to meat, lipid oxidation is the major cause of deterioration during subsequent storage. This is particularly the case for meats like chicken and lamb that contain significant amounts of unsaturated fatty acids. In general, HPP has little effect on lipid oxidation below 300 MPa, but can have a significant effect at higher pressures.

PEF is considered as a very promising non-thermal technique of preserving foods and improving food quality. As a non-thermal technology, PEF processing causes less degradation of nutritional and sensory characteristics

of foods than traditional thermal processing technologies (Buckow et al. 2013; Walkling-Ribeiro et al. 2010; Rivas et al. 2006). It exhibits many advantages such as lower treatment temperature, shorter processing time and potential continuous flow in comparison to traditional processing technologies (Puértolas, López, Condón, Álvarez, & Raso, 2010; Walkling-Ribeiro, Rodríguez-González, Jayaram, & Griffiths, 2011), making it a very appealing technology for food manufacturers. PEF processing does not cause side effects like severe structural and oxidative changes, and off-flavour development. Furthermore, it does not generate environmental hazards and there is no evidence of toxicity (Kumar, Patel, & Kumar, 2015; Pal, 2017). At high electric field strengths (>20 kV/cm), PEF has been shown to be lethal to many spoilage and pathogenic bacteria at or near atmospheric temperature (Zhao et al. 2013; Haughton et al. 2012; Moritz et al. 2012; Rodrıguez-Gonzalez et al. 2011) and can be used as an alternative to conventional thermal pasteurization processes to inactivate food microbes and quality related enzymes while retaining the nutritional, sensory and health-promoting characteristics of the products (Sanchez- Vega et al. 2014). While the technology has been recognized as a non-thermal technology, as its effects do not require heat, ohmic heating can be generated under high treatment intensity. While this can be useful for synergistic effect on microbial inactivation and can be controlled by rapid cooling post treatment, this can have negative effects on the quality and appearance of solid food materials similar to cooking effect in fresh meat (Bekhit et al. 2014). While tenderization, meat safety and accelerated curing appears to be the areas where PEF could provide attractive options in meat processing for meat industry (Bhat, Morton, Mason, & Bekhit, 2019). Moreover, this technology could be used to upgrade the less tender meat cuts by optimizing the technological inputs to different meat cuts and thereby optimize the product quality (Bekhit et al. 2016).

2.4.2. High-pressure processing (HPP)

High pressure processing (HPP) is an environmentally friendly alternative for pasteurization using pressure levels between 100 and 800 MPa at low or moderate temperature (lower than normal pasteurization and blanching temperatures) (Welti-Chanes et al., 2005).

2.4.2.1 HPP Principle

HPP is governed by the Chatelier's principle that involve temperature and pressure. Pressure can disrupt the structure of microorganisms, and change the stability of enzymes, chemical bonds, small molecules and lipids (Considine, Kelly, Fitzgerald, Hill, & Sleator, 2008; Rastogi, Raghavarao, Balasubramaniam, Niranjan, & Knorr, 2007). With increased pressure , temperature can also increase resulting in inactivation of enzymes and generation of off flavours (S Toepfl et al., 2006). The equipment is typically made up of high strength steel alloys with high fracture toughness and corrosion resistance (Ting et al., 2011). A typical high-pressure equipment is shown in Figure 8.

Figure 8 Industrial HPP equipment located at Food Bowl facility (Auckland, New Zealand)

During HPP processing, vacuum sealed packed food products (such as meat) are placed into a chamber (Figure 9). The vessel is then closed and filled with

transmitting fluids (such as water or food grade solution). After pressurizing, the vessel is opened, and the final products are unloaded. Oey, Lille, Van Loey, & Hendrickx (2008) stated that pressure applied on foods is transmitted uniformly and instantaneously, with minimal influence on the size and shape of fruit-and vegetable-based food products (Oey et al., 2008).

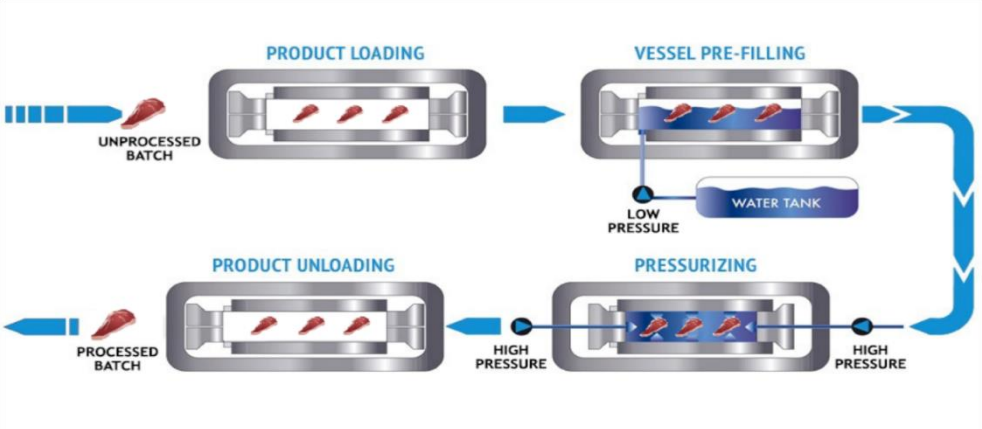

Figure 9 Diagram showing operation of a HPP unit. Source: http://www.hiperbaric.com/en/hpp

2.4.2.2 Impact of HPP on quality and functionality of meat

The application of HPP processing can cause several meat quality changes in terms of chemical properties, structure and texture of meat (Bajovic, Bolumar, & Heinz, 2012). Studies have demonstrated the effect of HPP on quality parameters of meat, such as colour changes in beef (Jung, 2003) and lipid oxidation in chicken breast (Beltran et al., 2003). A summary of HPP research carried out on meat and its products is shown in Appendix Ⅰ.

Colour

Studies have reported that HPP pressurization of meat can result in significant colour changes in fresh meat colour of chicken breast fillet (Rodríguez-Calleja, Cruz-Romero, O'Sullivan, García-López, & Kerry, 2012), beef (McArdle, Marcos, Kerry, & Mullen, 2010), pork (Souza et al., 2011) and lamb (McArdle, Marcos, Mullen, & Kerry, 2013).

Rodríguez-Calleja et al (2012) reported that pressurized chicken breast fillet at 300MPa for 5 min at 20°C significantly ($p < 0.05$) increased L*, a* and b* values compare to control samples. McArdle, Marcos, Kerry, & Mullen

(2010) investaged that the colour changes of post rigor beef (*M. pectoralis profundus*) muscles pressurized for 20 min at 200, 300 and 400 MPa, at 20 °C and 40 °C. They concluded that beef (*M. pectoralis profundus*) muscles pressurized at 200 MPa had a lower impact on colour parameters than higher pressurisation levels (300 MPa and 400 MPa). Souza et al (2011) evaluated the effect of HPP (215 MPa for 15 s, 33°C) on three different pork muscles (*M*. Longissimus, *M*. Psoas major and *M*. riceps brachii) colour. They reported that the CIE L* value of these three muscles was *significantly increased when HPP level increased from 0 MPa to 215MPa with holding time at 15 seconds, meanwhile* a* value was *significantly decreased in M*. Longissimus *and M*. triceps brachii*,* whereas b* value was only significantly increased in *M*. Longissimus *compare to control sample. T*he rare or medium rare steaks, or pinkish lamb will not be an option in samples treated at pressures above 200 MPa (Ma & Ledward, 2013). This was because pressurization of meat basically increases lightness and decreases redness due to protein denaturation or modification (McArdle et al., 2013). The increase in L* values ("whitening/ brightening") can be attributed to globin denaturation, heme release, ferrous ion oxidation and the changes in the water content (Cheftel & Culioli, 1997).

Texture

Pressure can also influence texture of meat by changing the myofibrillar protein structure and their gel-forming properties. Meat tenderization by HPP can be attributed to lysosome breakdown and subsequent proteolytic activity (Hugas, Garriga, & Monfort, 2002). HPP had different effects on shear force of various meat species, such as pork (Souza et al., 2011), beef (McArdle et al., 2010; Morton et al., 2017) and lamb (McArdle et al., 2013). McArdle et al (2010) reported that beef (M. pectoralis profundus) treated with HPP for 20 min (35-55°C) at 600 MPa resulted in higher Warner Bratzler Shear Force (WBSF) values compared to samples treated at 400 MPa. McArdle et al (2013) further showed that the WBSF values of lamb (M. pectoralis profundus) muscles was not significantly different between samples pressurised at 200 and 400 MPa for 20 min. Souza et al (2011) further

demonstrated that shear force was not different (P > 0.05) between control and HPP treated samples (215 MPa for 15 seconds) for the *M*. Psoas major or *M*. riceps brachii pork muscles, but was significant lower for *M*. Longissimus (more tender) compared to control. A recent study by Morton et al (2017) reported that shear force of beef (M. longissimus thoracis*) was significantly* decreased *with treatment at 250 MPa for 2 min compared to 175 MPa for 3 min.*

Lipid oxidation

It is well known that the application of HPP on meat can induce lipid oxidation and increase lipid oxidation level with increased pressure. Cheah & Ledward's (1996) investigated the effect of HPP (0-800 MPa for 20 min at 20 °C) on lipid oxidation of minced pork. The results indicated that the rate of lipid oxidation was slightly increased (p>0.05) from 0 to 200 MPa, but significantly increased for the samples treated at 300 MPa and above.HPP treatment at 215 MPa for 15 s, 33°C was found to inhibit the rate of lipid oxidation in pork loin (*M. longissimus dorsi*) compared to control (Souza et al., 2011). Several studies investigated the effect of pressure treatments on lipid oxidation of turkey thigh muscle (Dissing, Bruun-Jensen, & Skibsted, 1997) and chicken breast muscle (Beltran, Pla, Yuste, & Mor-Mur, 2003; Orlien, Hansen, & Skibsted, 2000) compared to heat treatment. Beltran et al (2003) concluded that chicken breast muscle pressure treated at 300 and 500MPa for 30min at 20°C resulted in little change in the nutritional value of meat products compared to thermal processing at 90°C for 15min. The chicken breast muscle treated at 800 MPa for 10min however enhanced lipid oxidation to the same extent as heat treatment (Orlien et al., 2000). They also demonstrated that chicken breast muscle exposed to pressures at or below 500 MPa showed no evidence of rancidity, similar to untreated meat during chilled storage. Ma et al (2007) and McArdle et al (2010) reported the increase in lipid oxidation values with pressure treatments of beef at pressures of ≥400 MPa compared to lower pressures. Furthermore, lamb (*M. pectoralis profundis*) pressurized at 400 and 600 MPa at 60 °C resulted in the highest TBARS values compare to control samples (McArdle, Marcos,

Mullen, & Kerry, 2013). Lipid oxidation may occur with HPP treatment due to: 1) accessibility of iron from hemoproteins that increases with disruption of membrane; 2) iron released from hemoproteins facilitate lipid oxidation (Bajovic et al., 2012).

Fatty acids

With lipid oxidation induced by HPP, some changes in individual fatty acids may occur. McArdle et al (2010) reported that high pressure had no effect on polyunsaturated/saturated fatty acid (PUFA/SFA) or omega 6/omega 3 (n6/n3) ratio of beef (M. pectoralis profundus*) muscle, but had* a significant effect on the sum of saturated (SFA), monounsaturated (MUFA) and polyunsaturated (PUFA) fatty acids. In contrast, the PUFA/SFA ratios of pressurized lamb (*M. pectoralis profundis*) muscles were significantly higher compared to control samples, but there were no significant effects on omega 6/omega 3 (n6/n3) ratios. Another research on Korean native black goat by Kang et al (2013) reported that fatty acids content was not significantly different between control and HPP treated samples.

Free amino acids

HPP can also modulate the proteolytic activities of meat to improve its quality. Ohmori et al (1991) reported that the free amino acids content of beef rounds significantly increased when meat was treated at 100-400 MPa compared to control samples. However, another previous research has established that no significant differences in the amino acids and peptide content of beef (Suzuki et al., 1994). They suggested that HPP had no adverse effect on the brothy and meaty flavours and cooked flavours of meat. However, pressurized chicken breast fillet at 300 MPa resulted in significantly reduced flavour, aroma strength and juiciness, and at 450 MPa produced breast fillets with the least aroma (Kruk et al., 2011).

Sensory evaluation

HPP was found to influence the flavour, juiciness and aroma of chicken breast fillet. Kruk et al (2011) reported that the 300 MPa pressure significantly reduced flavour, aroma and juiciness, with 450 MPa pressure

treatment resulting in the weakest aroma. Rodríguez-Calleja et al (2012) further demonstrated that pressurized chicken breast fillet at 300 MPa for 5 min were more acceptable, and had more chicken aroma attribute to panellists compared to control. Morton et al (2017) recently demonstrated that beef (M. longissimus thoracis) treated at 175 MPa did not influence the juiciness and flavour of the meat but the overall acceptability and eating scores were significantly improve. However, there are limited studies reporting on the sensory attributes of meat treated with HPP.

2.4.3. Pulsed electric field (PEF)

Pulsed electric field (PEF) is a novel non-thermal technology that has gained much attention recently. Most applications of PEF for food so far have been for microbial inactivation. PEF has been applied as a pretreatment for permeabilization of vegetable and animal tissue to enhance the efficiency of mass transfer of water or valuable compounds from biological matrices, demonstrating its efficiency in drying, extraction, and diffusion processes (Donsì, Ferrari, & Pataro, 2010). This method has also been widely used in the processing of liquid foods, such as fruit juices and milk for decades (Aronsson, Borch, Stenlöf, & Rönner, 2004; Grimi, Mamouni, Lebovka, Vorobiev, & Vaxelaire, 2011; Mosqueda-Melgar, Elez-Martínez, Raybaudi-Massilia, & Martín-Belloso, 2008). However, there has been increasing number of studies on the application of PEF on solid food such as meat (Barbosa-Cánovas & Altunakar, 2006; Bekhit et al., 2014; Faridnia et al., 2014; O'Dowd et al., 2013).

2.4.3.1 PEF Principle

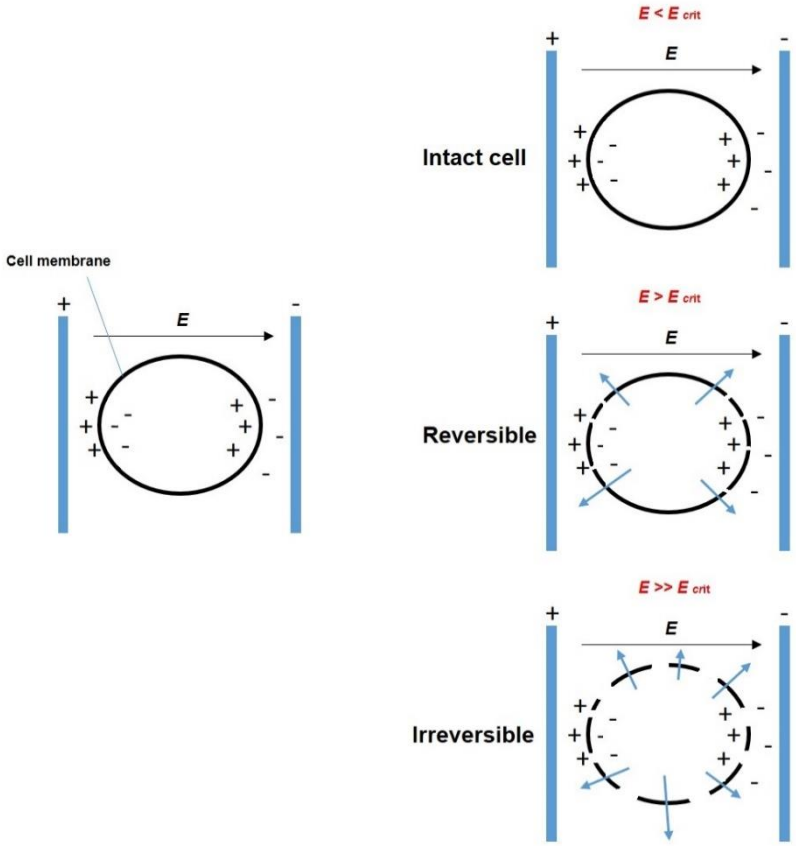

Figure 10 Schematic depiction of the mechanism of membrane permeabilization by electrocompressive forces induced by an external electric field. E = Electric field strength, Ecrit = Critical electric field strength (Stefan Toepfl, Heinz, & Knorr, 2005)

The permeability of cell membranes can be modified when cells are exposed to an electric field, and as a consequence cell structure may change and local membrane disrupted. This phenomenon, called electroporation, has led to further studies into the applications of PEF in food- and bioprocessing. Sale & Hamilton (1967) and Zimmermann, Pilwat, & Riemann (1974) stated that an electroporation of biological membranes can be achieved by exposure to an external electrical field. Figure 10 showed that when E values close to the Ecrit, reversible permeabilization occurs allowing the cell membrane to recover its functionality and structure. With more intense PEF treatment (electric field strengths higher than the critical value) applied, large irreversible membrane pores may be formed (S Toepfl et al., 2006).

The main processing parameters in PEF treatments include electric field strength (*E*), pulse shape, pulse width (τ), treatment time (*t*), number of pulses, pulse specific energy, and frequency (*f*). According to Raso-Pueyo & Heinz (2010), electric field strength, pulse energy, and treatment time are the basic control parameters of PEF processes, whereas width and frequency of the pulses contribute to defining the process time. Faridnia, Bekhit, Niven, & Oey (2014) reported that increasing the electric field strength can result in an increase in treatment efficiency. The dielectric strength of food material is limited between 60 to 80 kV/cm (Ho & Mittal, 2000). For muscle material, Lopp & Weber (2005) reported that application of PEF with higher electric field strength (3.5 kV/cm, 20 Hz, 100 pulses) significantly decreased shear force values of beef *triceps brachii*. Increasing electric field strength from 0.27 to 0.56 kV/cm (3.4 to 40.7 kJ/kg) was reported to increase the tenderness of beef *semimembranosus and longissimus lumborum* muscles (Bekhit, van de Ven, et al., 2014). Bekhit, Suwandy, Carne, van de Ven, & Hopkins (2016) suggested that high-intensity PEF treatment can result in protein denaturation of hot-boned beef *longissimus lumborum* muscles.

Although PEF is claimed as a "non-thermal" treatment, it can cause moderate temperature rises (ΔT) (O'Dowd et al., 2013). The increased in temperature can significantly affect the fluidity and stability of cell membrane. For example, the phospholipid structure of the cell are a gel-like structure at low temperatures, but the order state will decrease when temperature increased (Stanley, 1991). However, McDonnell, Allen, Chardonnereau, Arimi, & Lyng (2014) reported that PEF treatment with 2.3 kV/cm did not always result in large temperature rises with the salting of pork. Faridnia et al (2014) also reported that beef meat treated with PEF (0.2–0.6 kV/cm, 1–50 Hz, 20 µs) did not change electrical conductivity and temperature. Medium conductivity κ (T) is an another key parameter for PEF processing, which is the ability of a material to conduct an electrical current (Reitler, 1990). Several research reported that the temperature of pork (Toepfl, 2006) and beef (O'Dowd et al., 2013) muscles increased with

increasing conductivity. An increase in electrical conductivity could be related to cellular damage. Faridnia et al (2014) reported that PEF enhanced transport of ionic contributed towards modification of the intracellular environment of beef samples which result in increased conductivity.

2.4.3.2 Impact of PEF on Quality and Functionality of meat

The application of PEF technology can potentially either improve functional properties of food or assist in the development of new products (S Toepfl et al., 2007). For example, PEF can induce changes in physical properties of meat such as structure and texture. Knorr et al (2013) also stated that PEF technology can be applied as a method for cell disintegration. PEF technology has been widely used to process liquid products with low electrical conductivity and viscosity, such as apple juice, liquid egg, milk, and orange juice (Mohamed & Eissa, 2012). Recently, there has been increasing applications of PEF technology applied to muscle food (appendix Ⅱ).

Colour

There are limited studies on how meat colour and its stability are influenced by PEF processing. Arroyo, Lascorz, et al (2015) and Faridnia et al (2015) reported no PEF effects on a* and b* colour values of *M.semitendinosus and M.longissimus thoracis et lumboru* beef, respectively. Alahakoon, Faridnia, Bremer, Silcock, & Oey (2016) in their book chapter concluded that the influence of PEF on meat color can be attributed to increase in temperature as a result of PEF treatment. Another study also demonstrated that the L* value of beef *M. semitendinosus* muscle samples was only affected by the temperature induced by PEF treatment (electric field strength: 1.9 kV cm^{-1}; energy density: 83.6 kJ/kg, frequency: 65 Hz and pulse number: 250) (O'Dowd et al., 2013).

Texture

The application of PEF in meat (especially beef) can enhance cell permeability due to electroporation and consequently enhance proteolysis that contributes to tenderisation (Bekhit, van de Ven, et al., 2014; Lopp &

Weber, 2005; Suwandy, Carne, van de Ven, Bekhit, & Hopkins, 2015a). Jaeger, Balasa, & Knorr (2008) and Topfl & Heinz (2007) reported that PEF treatment successfully accelerated curing and drying by reducing the time required to carry out ham curing. The PEF impact on the meat tenderization involve a number of different interrelated mechanisms. PEF processing has been shown to physically disrupt muscle structure, and enhance the denaturation and solubilization of meat proteins (Warner et al., 2017). With electroporation, the release of cell constituents from muscle fibers increases, resulting in proteolysis and glycolysis in the muscle cells (Alahakoon et al., 2016). Bekhit, van de Ven, et al (2014) further showed that PEF treated meat had increased fragmentation of myofibrils. The increased cellular permeability can also lead to the release of the calcium ions required for the activation of calcium-dependent proteases such as μ-calpain which also accelerates proteolysis (Lee, Joo, & Ryu, 2010). Meat tenderness have been reported to be improved by PEF treatment of *M. semitendinosus* beef (Faridnia et al., 2015; O'Dowd et al., 2013), *M. semimembranosus and M. Longissimus lumborum* beef (Bekhit et al., 2016), and turkey breast meat (Arroyo, Eslami, et al., 2015). However, no previous study has investigated the effect of PEF processing on the textural sensory properties of meat.

Lipid oxidation

Lipid oxidation is attributed to the disruption of muscle cell membranes that facilitate the interaction of unsaturated fatty acids with prooxidant substances (Tichivangana & Morrissey, 1985). Any disruption to cell membranes can facilitate the migration of pro-oxidants and free radicals to unsaturated fatty acids and expose phospholipids of cell membranes to oxidation (Buckley, Morrissey, & Gray, 1995). The generation of free radicals and hydroperoxides from unsaturated fatty acids can further break into secondary products, which are responsible for off-flavors and odors and can reduce meat nutritional quality. Arroyo reported no influence of PEF treatment (1.1-3 kV/cm) on lipid oxidation of turkey meat after 5 days of

storage. TBARS value was not affected by PEF with field strength (1.2 or 2.3 kV/cm) in *M.Longissimus thoracis etlumborum* pork (McDonnell et al., 2014). Moreover, oxidative stability of beef (*M.Longissimus lumborum*) treated with field strength from 0.58 to 0.73 kV/cm did not change. It can be seen that no effect of PEF on the oxidative stability of meat has been reported due to the low field strength applied in previous studies. However, significantly increased lipid oxidation was found in frozen-thawed beef *M.semitendinosus* (Faridnia et al., 2015). The process of freeze thaw can increase TBARS accumulation, further damage cell membranes due to ice crystals in muscle, followed by the release of pro-oxidants, especially haem iron (Benjakul & Bauer, 2001). Danowska-oziewicz (2009) stated that the extent rate of lipid oxidation was related to the meat composition (fatty acids), the presence of antioxidants, temperature, and other processing conditions. PEF treatment may cause other unfavorable changes in the meat depending on processing conditions. There have been very few publications on the effect of PEF on the oxidative stability of beef. Parameters such as chilling and freezing as a pre- and post- treatment, storage conditions, all have the potential to increase the lipid oxidation of PEF-treated meat. However, PEF treatment on chilled beef *longissimus thoracis et lumborum* and *semitendinosus* muscles has been reported not to show an increase in lipid oxidation (Arroyo et al. 2015b; Faridnia et al. 2015) but significantly increased lipid oxidation of frozen-thawed beef (Faridnia et al. 2015; Ma et al. 2016).

Fatty acids and volatile compounds

The effect of PEF on fatty acids content has only been reported by Faridnia et al. (2015). They found that the PUFA/SFA and omega-6/omega-3 ratio of beef (*M. semitendinosus*) remained within the recommended levels. They also reported that PEF processed frozen thawed samples affected the volatile profile of meat by increasing the protein and lipid degradation products such as dimethyl disulfide and 2, 3-octanedione. There are limited

studies examining the effects of PEF processing on free amino acids content and sensory attrinbutes of meat.

2.5. Temporal Dominance of Sensations

Sensory characteristics like appearance, texture, juiciness, and flavour, influence the consumers' perceived quality and acceptability of meat products. Several approaches have been used to investigate the eating quality attributes of meat and meat products. This include the use of surveys (Hoffman et al., 2005), consumer sensory testing (Lagerstedt et al., 2008), descriptive analysis (Corbin et al., 2015; Oltra et al., 2015), and time-intensity (TI) analysis (Lorido et al., 2016). Temporal Dominance of Sensations (TDS) is advantageous for studying the temporal changes of food sensory characteristics in the mouth. Panellists choose from a list of attributes, the dominant sensory sensation, and rate the changes in dominant attributes over consumption time (N. Pineau et al., 2009). TDS has been widely used on different types of foods (liquid, semi-solid or solid) (Appendix III).

TDS methodology has only been used in two studies to determine changes in sensory perception of meat. Devezeaux de Lavergne, Derks, Ketel, de Wijk, & Stieger (2015) used TDS to determine the dynamic texture perception of sausages. Results showed that differences in eating behaviour between subjects can change bolus properties of sausages resulting in differences in dynamic texture perception of the same sausage. In another research, TDS and time-intensity (TI) were used to estimate the influence of salt content on the flavour of montanera and concentrate (normal salt and reduced salt) dry-cured ham (Lorido et al., 2016). The result showed that salt reduction did not have a marked effect on TI analysis for most of attributes between normal salt and reduced salt dry-cured ham, especially in concentrate dry-cured ham. However, TDS curves demonstrated some the difference between normal salt and reduced salt of concentrate dry-cured ham. As the result, hardness and fibrousness showed a significantly higher % StdDuration ($p < 0.05$) in normal salt samples compared to reduced salt

ones, while cured flavour presented a significantly higher StdDuration% ($p < 0.01$) in reduced salt samples compared to normal salt ones.Braghieri et al (2016) further used TDS combined with quantitative descriptive analysis (QDA) to evaluate the sensory properties of Lucanian dry-sausages with either added nitrate, nitrite and l-ascorbic acid (NS), or not (NNS). QDA result showed that NNS products were significantly harder ($P < 0.05$), with higher intensities of flavor ($P < 0.10$), pepper ($P < 0.20$), and oiliness ($P < 0.20$), and lower chewiness ($P < 0.20$). TDS results showed that hardness was the first dominant attribute in NNS products. Flavor then remained dominant until the end of tasting. However oiliness was the dominant attribute in NS products. This research indicated that TDS provided additional information for the description and differentiation of Lucanian sausages.

2.5.1. TDS curves

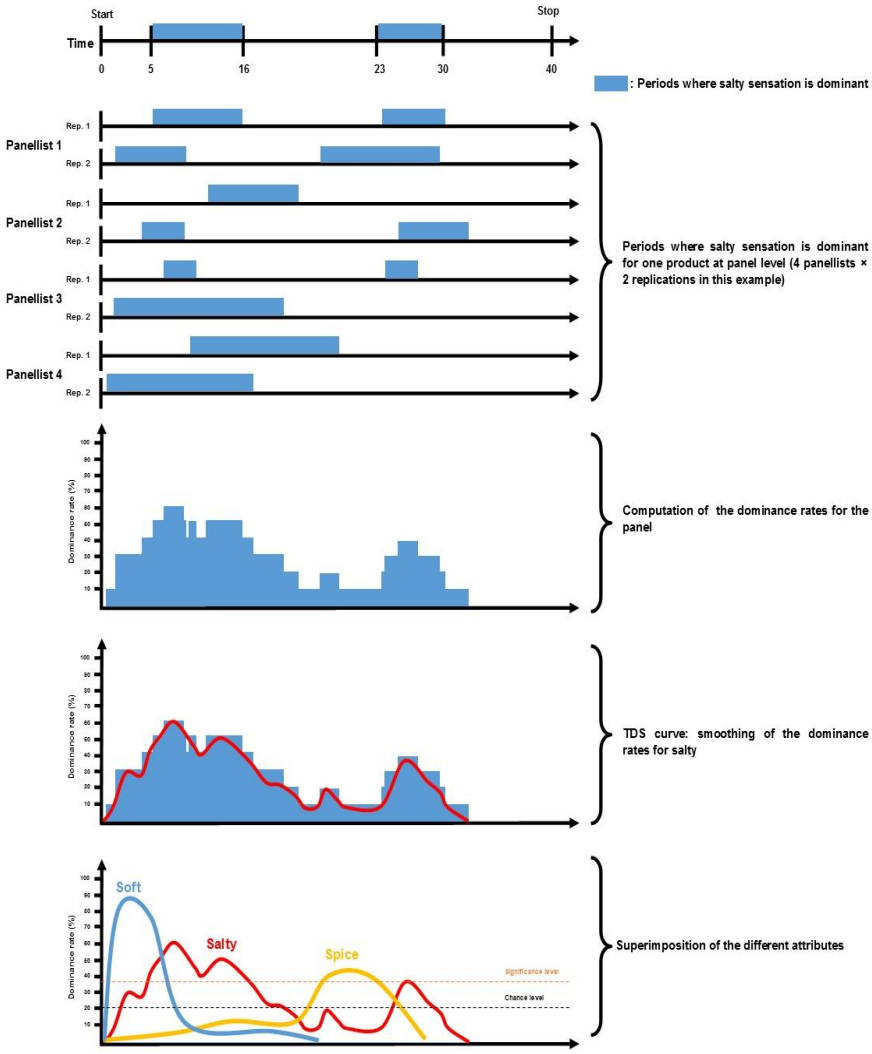

Figure 11 Methodology to compute TDS curves

According to Pineau et al (2009), the TDS procedure considers each sensory attribute separately. The dominance of given attributes was assessed as over time. The proportion of runs (subject × replication) for attributes assessed as being dominant is calculated and smoothed using the FIZZ software (version 2.46b, Biosystems, Counteruon, France). These proportions are plotted against time in TDS curves. These curves depict the proportion of panellist who selected the attribute as dominant at a given time. The higher the dominance rate for the attribute, the better the agreement among panellist. Figure 11 shows a TDS curve for sausages containing different NaCl concentrations (Paulsen, Nys, Kvarberg, & Hersleth, 2014). Soft was the first

dominant sensation with the dominance rates starting at over 40% dominance rate and then decreasing to below chance level in less than 10 s. Dominance rate of salty increased from almost the start of mastication and reached significance level after 5 s, and decreased to below chance level at 16 s of the mastication period. Starting from 20 s, spice became the dominant attribute above significance level until 23s of mastication.

2.5.2. Data analysis for TDS curve

The dominance rate of each attribute is plotted against time in a TDS curve. Dugas, Pineau, & Folmer (2012) applied graphical comparison for TDS data analysis, which only records the most dominant attribute for each sip from a cup containing espresso. Pineau, Cordelle, & Schlich (2004) developed an approach to convert the TDS curve result sinto TDS score and then compared it to the sensory profiling result. Labbe et al (2009) further proposed the use of covariance Principal Component Analysis (PCA) based on TDS scores. TDS score takes into account the intensity and duration of every elicitation of a given attribute over the time of evaluation. This score value is therefore the average of scores given to an attribute during an evaluation weighted by their duration, as shown in the equation below:

$$\text{Score} = \left(\sum_{\text{scoring}} \text{Intensity} \times \text{Duration}\right) / \left(\sum_{\text{scoring}} \text{Duration}\right.$$

The scores given to descriptors through the TDS procedure can be averaged across products and can be performed through PCA on the products x descriptors matrix of the mean intensities for all subjects and all times. PCA gives a sensory map which can be easily compared with the maps obtained with other sensory methodologies. This statistical method has been used for analyzing TDS data of blackcurrant squashes (Ng et al., 2012) and yogurt (Bouteille et al., 2013; Bruzzone, Ares, & Giménez, 2013). However, Peltier, Visalli, & Schlich (2015) suggested that PCA carried out using mean scores of products does not take into account the variance in product mean scores arising from variability between individual panelists. Canonical variate analysis (CVA) is a multivariate technique related to multivariate analysis of

variance (MANOVA), which can overcome PCA limitations (Mardia, Kent, & Bibbly, 1989). CVA has been employed for analysis of TDS score in water (Teillet, Schlich, Urbano, Cordelle, & Guichard, 2010), red wines (Meillon, Urbano, & Schlich, 2009) and white wine (Sokolowsky & Fischer, 2012).

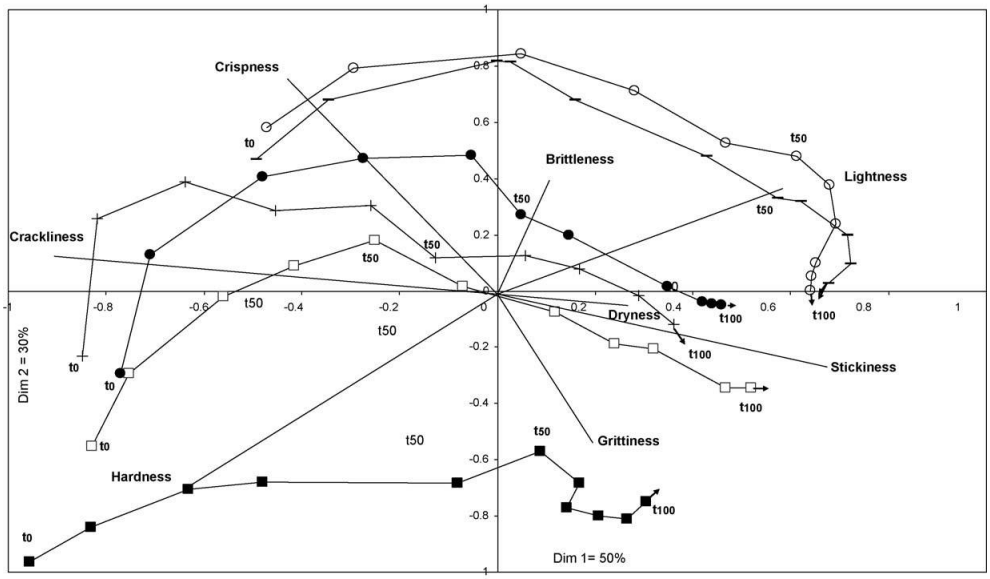

Figure 12 PCA. Biplot representing the texture trajectories of the six wheat flakes over the mastication period (□Wheat flakes A, ■ Wheat flakes B, – Wheat flakes C, ○ Wheat flakes D, ● Wheat flakes E and + Wheat flakes F) (Lenfant, Loret, Pineau, Hartmann, & Martin, 2009)

TDS trajectory mapping can be used to visualize the evolution of product sequences in the sensory space, called the trajectory (N Pineau & Schilch, 2015). Lenfant et al (2009) and Devezeaux de Lavergne et al (2015) selected the dominance rates at different time points and ran covariance PCA to correlate between variables and sensory attributes of wheat flakes and semi-solid food gels, respectively. For example, six products and eight attributes were evaluated by Lenfant et al (2009). Dominance rates of the individual sample were equally split into 11-time points to represent 0%, 10%, 20%… 100% of the mastication period. As seen in Figure 12, there were 11 points of time for each product: the first score (t0) is the beginning of a sensory trajectory, and the end point (t100) corresponded to the last score before swallowing. The trajectory PCA allowed visualization of the global pattern of all products, starting either hard, crackly or crispy, and finishing either light, sticky or gritty (N Pineau & Schilch, 2015). The authors concluded that a natural hierarchy of perceptions existed with crackly, if

perceived as dominant, will always be perceived at the beginning, whereas sticky will always be perceived at the end of mastication period. This methodology was successfully applied to understand changes in texture of products during consumption. It is also possible to plot the trajectory map using flavour or aroma attributes. However, the patterns were less obvious than for texture, and less easy to read (N Pineau & Schilch, 2015).

Chapter 3. Materials and Methods

3.1. Questionnaire development and data collection

The conceptual framework by Hoffman, Muller, Schutte, Calitz, & Crafford (2005) to investigate the expectations, perceptions and purchasing behaviour of consumers of game meat was adapted for use in this study (Figure 13). The structured, self-administered questionnaire was developed to investigate consumer perception and purchase intention of lamb meat in China.

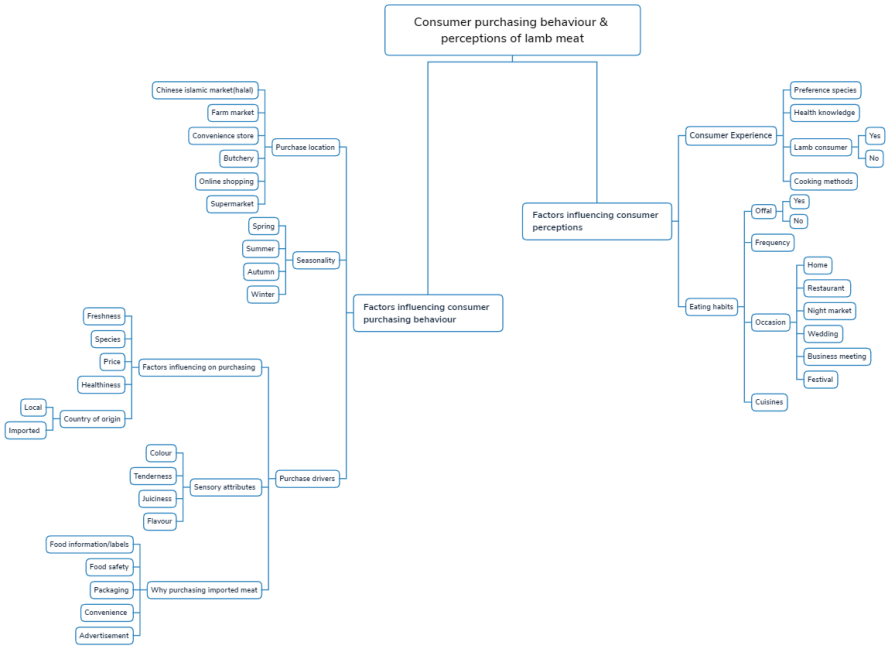

Figure 13 Dendogram developed to quantify consumer purchasing behavior and perception of lamb meat (adapted from Hoffman et al, 2005)

A total of 31 questions were designed (Table 3). Thirteen questions were related to Chinese consumer perception of red meat. These questions included consumer experience and eating habits. Ten questions were related to Chinese consumer purchasing behaviour of lamb meat. These questions included purchase location, seasonality, sensory attributes and purchase drivers. Finally, eight questions related to socio demographic characteristics that included age, race, gender, income, occupation and education level, and gender, were also collected.

Table 3 Questionnaire on Chinese consumer perception and purchasing behaviour of meat

Consumer Perception[1]
Experience
What do you think of meat and meat products from New Zealand?[2]
Which type of red meat do you prefer?
Why do you prefer beef/lamb/pork/mutton?
Which type of meat is healthier?
Which one of following has more cholesterol?
What is the reason you do not like lamb/mutton?
Are you lamb consumer?
Why do you prefer lamb over mutton?
How do you cook lamb meat?[3]
Eating habits
Do you eat lamb offals?
How often do you eat lamb/mutton?
Where would you like to eat lamb?
What lamb cuisine do you consume when you eat out?[3]
Consumer purchasing behaviour[1]
Purchase drivers
What is your priority criterion when purchasing meat?
What price would you pay for uncooked lamb/mutton meat?
What would you prefer to purchase if mutton and lamb were the same price?
Which sensory attributes are important when purchasing lamb?[3]
What is the origin of the meat do you prefer to consume?
Why do you prefer imported meat?
Where do you purchase lamb meat? [3]
Purchase location
Would you purchase lamb with the following food certification?
Seasonality
Which season would you like to purchase lamb? [3]
Country of origin
Comparisons of local lamb meat (Mongolia, Xinjiang) and imported lamb meat from different countries (New Zealand, Australia, Uruguay, Others)[4]

[1]Single apply; [2] word or phase description;[3] Check all that apply;[4] 9-point Likert scale (1: "strongly disagree", 9: "strongly agree") Comparisons were based on perceptual quality, reliable, superior sensory, appearance, reputation, expensive, natural and healthy, value for money and Willingness to purchase (WTP)

At the start, a focus group of ten people from the different regions of China were recruited to discuss their perception of buying and consuming NZ meat products. The questionnaire was developed in English, and subsequently translated to Chinese. To improve the clarity and explicit of the survey questions, a pre-test was carried out by the focus group of 20 participants. A convenience sample (n = 601) of Chinese consumers from different parts of China (urban) were then recruited via social media (Wechat, email, and

QQ) to complete a self-administered questionnaire comprising of the 31 questions. Data were collected using an online survey through a website http://www.sojump.com. Participants who did not consume meat were excluded from the study.

3.2. Preparation of meat samples for HPP and PEF

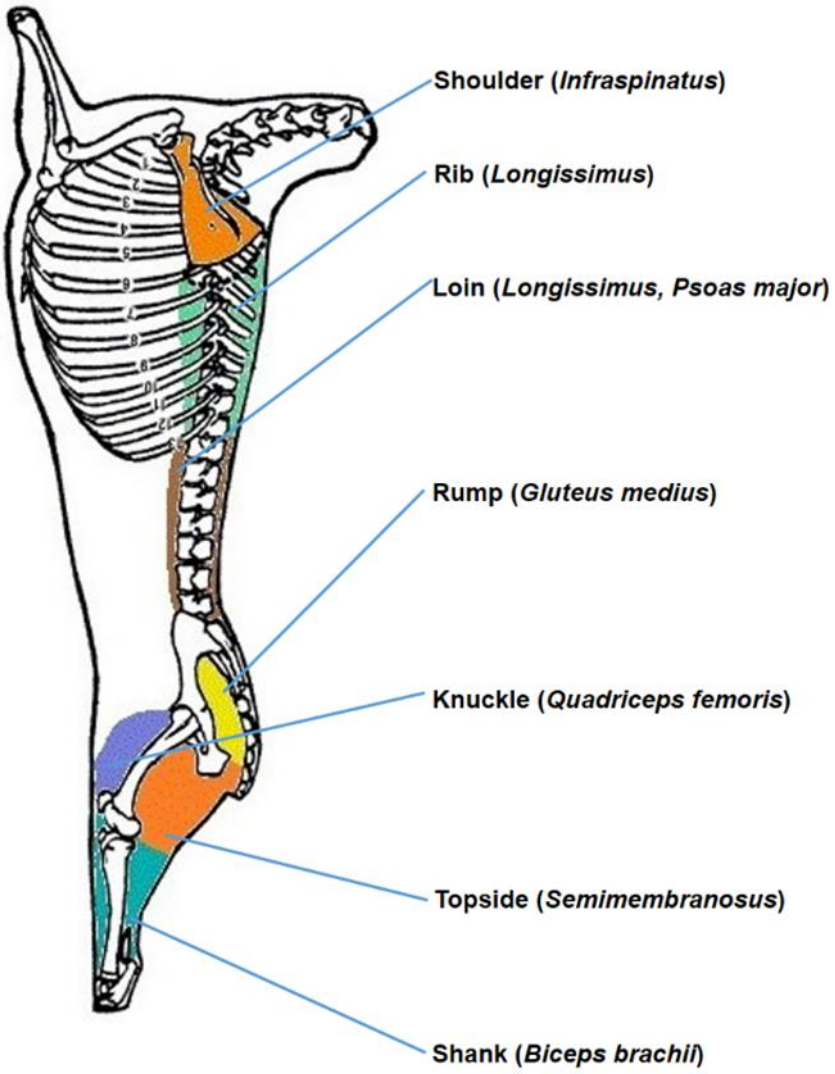

Figure 14 lamb meat cuts were used for this study

3.2.1. High pressure processing (HPP)

Frozen lamb meat cuts, shoulder, loin and shank (Fig. 14), were obtained from four animals (mean cold carcasses weight of 140.5–150.5 kg) at 48 h post-mortem from AgResearch (Hamilton). These cuts were used for HPP processing. After thawing overnight, each cut was individually packed and

hermetically sealed in high density polyethylene bags at 4 °C before HPP processing (n=3).

3.2.2. Pulsed electric field processing (PEF)

In this study, high-value lamb meat cuts (shoulder, loin and rib) and low-value cuts (knuckle, rump, shank and topside) that were either chilled or frozen were used (Fig. 14). The chilled meat cuts from four lambs were purchased from New World supermarket, Dunedin. Chilled meat was stored at 4 °C before PEF processing. Lamb meat was obtained 48 h post-mortem and cold carcasses weight between 140.5–150.5 kg. Frozen shoulder, loin, rib, knuckle, rump, shank and topside lamb cuts, (Fig. 14), were obtained from four animals (cold carcasses weight of 140.5–150.5 kg) at 48 h post-mortem from AgResearch (Crown Research Institutes, Hamilton). Frozen-thawed meat was vacuum packed and stored at −20 °C for about 2 months prior to use. Prior to PEF processing, the frozen samples were thawed overnight at 3±1 °C (air velocity 0.25m/s).

3.3. High pressure processing (HPP) parameters

Pressurization of lamb cuts was conducted using an industrial scale HPP equipment (HPP 055, Multivac, Multivac Sepp Haggenmüller GmbH & Co., Wolferschwenden, Germany). Water was used as the pressure-transmitting medium, with an initial temperature of around 7-8◦C. The temperature reached after pressure build-up was less than 25◦C. The rate of pressure build-up was conducted at 125 MPa/min. Vacuum packed lamb samples were loaded in a cylindrical loading container and HPP-treated at 200, 300, 400, and 600 MPa. Water temperatures after pressurization were 14◦C, 21◦C, 28◦C and 42◦C, respectively. Pressure was held for one minute once the targeted pressure was achieved. After depressurisation, all samples were transported and stored at - 20 °C for further analysis.

3.4. Pulsed electric field processing (PEF) parameters

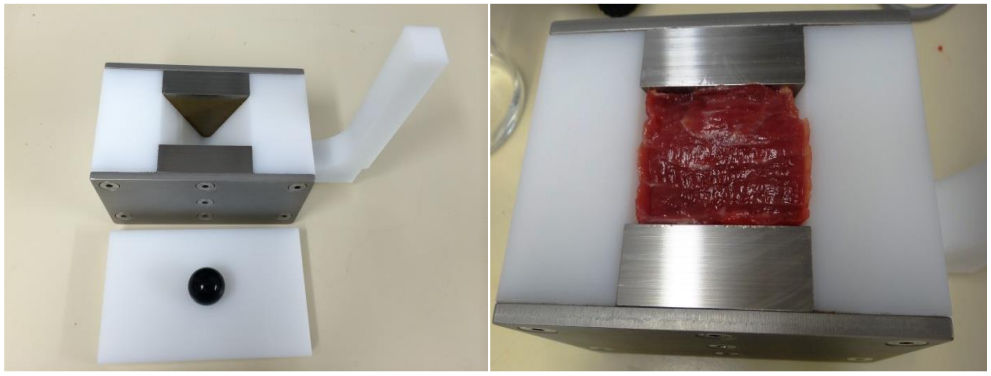

Figure 15 Treatment chamber used in the present research. The lamb samples were cut to fit the PEF treatment chamber

A PEF batch treatment chamber (6 cm height × 4 cm width × 6 cm length) was used to hold the samples (Figure 15). Stainless steel parallel electrodes were used with a distance gap of 4 cm. A special cutting mold with the same dimensions as the PEF chamber was used to cut the meat. The meat was the carefully positioned between two electrodes to ensure direct contact between the meat samples and electrodes in the PEF chamber. The lamb samples were processed in a pilot plant scale PEF system (Elcrack-HPV 5, DIL Quakenbruck, Germany).

Both chilled and frozen-thawed samples were divided into two groups. One group was subjected to pulsed electric field (PEF) treatment (chilled-PEF and frozen-thawed PEF), and another retained as non-PEF treated 'control' sample (chilled-control; frozen thawed control). Muscles were cut parallel to the fiber direction to fit the PEF chamber for both control (no PEF) and PEF treated samples. Control samples were chilled and frozen lamb samples without PEF treatment. The fiber direction was adjusted in such a way that it was perpendicular to the electric current. The weight of sample was approximately 62 ± 5 g. Each treatment for each lamb muscle was conducted in 6 replicates independently. After each treatment, muscle sample was vacuum packed in polyethylene plastic bags and immediately stored at 4 °C for 0 and 7 days storage. Samples were then stored at −20 °C before further analysis. The operating tempture were monitored using Tinytray data logger

(Gemimi Data loggers Ltd, Keol Track Inc, Chichester, WS,UK) during aging/ freezing/ thawing process.A preliminary experiment was carried out to determine the PEF processing parameters that resulted in no electrical arcing to samples during PEF treatment. This was done by assessing the visual quality of samples immediately after PEF treatment, and determining the stability of current delivery. Lamb samples (chilled and frozen-thawed) were treated at the electric field strength of between 1–1.4 kV·cm^{-1}, specific energy of 88– 109 kJ·kg^{-1}, pulse width of 20 μs, frequency of 90Hz, and a pulse number of 964 (Table 1). The pulse shape (square wave bipolar) was monitored online using an oscilloscope (Model UT2025C, Uni-Trend Group Ltd., Hong Kong, China) during PEF treatment. The temperature of samples before and after treatments were monitored using temperature loggers (Grant Squirrel SQ800, Cambridgeshire, UK). The initial temperature was maintained at 4 °C.

3.5. Electrical input, pH, temperature and electrical Conductivity σ for PEF processing

PEF treatment parameters included field strength, pulse peak energy, current and power, pulse count, resistance, energy, as well as calculated field strength and specific energy that were recorded when utilizing the PEF equipment for each treatment. The energy density was calculated as described by Zhang, Barbosa-Cánovas, & Swanson (1995).

$$\text{Wspec}\ (\frac{kJ}{kg}) = \frac{V^2(n\tau)}{RW}$$

V is the pulse peak voltage (in kV), n is the number of pulses applied (dimensionless), τ is the pulse width of square pulses (in microsecond), R is the effective load resistance (in ohm) and W is the weight of sample (in kilogram) to be treated in the PEF treatment chamber.

Duplicate measurements were conducted for pH, temperature and electrical conductivity of each sample directly before and after PEF treatments. The

temperature was monitored using a temperature logger (Grant Squirrel SQ800, Cambridge, UK) and type T thermocouples. The initial temperature was maintained at 4 °C and the pH of each meat sample was measured using a combination puncture pH electrode (InLab 427, Mettler-Toledo Process Analytical Inc., Wilmington, MA) attached to a pH-meter (Hanna HI 98140, Hanna Instruments, Woonsocket, USA). A hand-held meat conductometer (LF-STAR, R. Mathäus, Pöttmes, Germany) was used to determine the change in electrical conductivity (σ) by inserting the twin probes directly into the samples.

3.6. Colour stability and cooking loss

The samples were thawed at 4 °C for 24 h before cooking according to the sous vide protocol described by Ma et al (2016). Thawed samples were heated in a water bath (Model 360, Contherm, New Zealand) at 58-59 °C for 2 hours. A Hunter lab (45/0, Colour flex) colorimeter was used to measure the meat color variables: lightness (L*), redness (a*), yellowness (b*), and total color difference (ΔE*). The samples were cut into cubes (2cm × 2cm × 2cm) and placed in a covered petri dish that was placed at the top of the colorimeter lens (n=3).

Samples were weighed before and after cooking. Cooking loss (%) was determined by using the formula below (Bekhit, van de Ven, et al., 2014):

$$\text{Cooking loss } (\%) = 100 \times (1 - \text{weight after cooking/weight before cooking})$$

3.7. Determination of lipid oxidation using TBARS

The extent of lipid oxidation in meat samples was measured using the Thiobarbituric acid reactive substances (TBARS) method as described by Nam & Ahn (2003). Minced meat (5 g) was homogenized with 15 mL of deionized distilled water using a homogenizer (L5M-A Laboratory Mixer, Silverson®) at 14,000 rpm for 30 s. One milliliter of the meat homogenate was transferred to a test tube and 50 µL of butylated hydroxytoluene (7.2% w/v in ethanol) and 2 mL of thiobarbituric acid (TBA)–trichloroacetic acid

(TCA) (20 mM TBA in 15% (w/v) TCA) were added. The mixture was vortexed and then incubated in a boiling water bath for 15 min to develop colour. Then samples were subjected to cooling for 10 min, and vortexed before being centrifuged for 15 min at 2500 xg. The absorbance of the resulting upper layer was measured at 531 nm against a blank prepared with 1 ml deionised water and 2 ml TBA/TCA solution. The amount of TBARS was expressed as milligrams of malondialdehyde per kilogram of meat. A standard curve was constructed using tetraethoxypropane (ranging from 41.76- 62.64 mmol/l) and mean values were obtained for triplicate samples (n = 3).

3.8. Determination of fatty acids

Fatty acid methyl esters (FAME) were determined according to De La Cruz Garcia, Lopez Hernandez, & Simal Lozano (2000). Fifty milligrams of a ground, freeze-dried sample (48 hours) was measured into a 4 ml amber vial. A 10µl aliquot of tridecanoic acid (2 $g.l^{-1}$) was added as an internal standard. Toluene (490µl) and freshly prepared 5% methanolic HCl (750µl) were added before filling the vial with nitrogen. After incubation in the water bath at 70°C (2 h), vials were cooled to room temperature before 6% aqueous K_2CO_3 (1ml) and toluene (500µl) were added. After centrifugation at 1100*g* for 5 min, the top layer was removed using a glass Pasteur pipette for FAME analysis.

Derivatized methyl esters of fatty acids were separated and quantified using a Shimadzu GC 2010 with a Flame Ionisation Detector. The column used was a 0.25mm x 30m x 0.25µm film thickness, fused-silica column (ZB-WAX, Phenomenex, USA). Nitrogen was used as the carrier gas, with a split ratio of 50, a head pressure of 8.7PSI, and 1 mL/min column flow. The injector temperature was set at 250 °C. The initial oven temperature was programmed at 140 °C, then increased to 245 °C at 5 °C/min, and held at 245 °C for 15 min. Thirty-seven FAME standards (Supelco product 47885-U) obtained from Sigma-Aldrich (Sydney, Australia) were serially diluted to six

concentrations (from 10 to 0.3125g.l^{-1}), and the standard calibration curve constructed was used for quantitative analysis.

3.9. Determination of free amino acids

The EZFaast^{TM} amino acid analysis kit (Phenomenex, Macclesfield, UK) was used for the analysis of amino acids using GC-FID according to manufacturer's instructions. Meat sample (0.1 g) was mixed with 1mL of methanol in an Eppendorf tube. The mixture was vortexed and then centrifuged at 2000 xg for 2 mins. The aqueous portion was retained for further analysis. The EZ: faast™ amino acid analysis kit (Phenomenex, Torrance, CA) was used to extract and derivatize the free amino acids of all lamb samples. Sample extracts were then analysed using a Shimadzu GC-2010 fitted with a flame ionization detector (Kyoto, Japan), and Zebron ZB-AAA GC column (5%-phenyl-95%-dimethylpolysiloxane phase, 30 m × 0.53 mm × 1.50 µm) (Phenomenex, Inc, USA). Nitrogen was used as the carrier gas and pressure was set to 60 Pa with a 2.3 ml/min column flow rate. The oven was started at 40 °C, increased to 110 °C at 50 °C/min, then to 320 °C at 20 °C/min, and held at 320 °C for 2 min. Norvaline (0.2mmol/l) was used as an internal standard and calibration curves of 17 amino acids (Ala, Gly, Thr, Ser, Pro, Glu, Asp, Val, Leu, Ile, Met, Phe, Lys, His, Tyr and Trp) were used for quantification. Samples were analysed in triplicates.

3.10. Determination of volatile profile using headspace/HS-SPME analysis

Frozen lamb meat sample was thawed overnight at 4 °C, and minced used by a coffee and spice grinder (Breville, Australian). Minced lamb meat sample (0.5 ± 0.1 g) was placed in a 10 ml flat bottom headspace vial fitted with a PTFE/ silicone septum and crimp cap (Supelco Co., Bellefonte, USA). Cooked lamb meat flavour was determined by heating the headspace vial using a plate heater at 80 °C for 5 min. After cooling down for 5 min, 10 µL of an internal standard (1, 2-dichlorobenzene in methanol, 600 ppm, Sigma Aldrich) was added into 125 µL insert by using a HPLC syringe.

Volatile extraction by HS-SPME was carried out according to the modified method of Ma et al. (2008). A divinyl benzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) fibre 50/30 µm (Supelco, Bellefonte, PA, USA) was used to extract headspace volatiles from meat. Prior to use, the fibre was conditioned following the manufacturer's recommendations. Volatile extraction by HS-SPME was carried out using a MultiPurpose Sampler MPS (Gerstel, Germany). The vial was maintained at 60 °C in the oven during the entire extraction procedure for 30 min. Each sample was run in triplicates.

The Trace GC Ultra (Thermo Scientific, Waltham, MA, USA) gas chromatograph was equipped with a DSQ series mass spectrometer (Thermo Scientific, Waltham, MA, USA). The GC-MS was installed with a VF-5 ms low bleed/MS fused-silica capillary column (5%-phenyl-95%-dimethylpolysiloxane phase, 60 m × 0.25 mm × 0.25 µm) (Phenomenex, Torrance, CA, USA). Helium was used as a carrier gas with a constant flow rate of 1.5 ml/min in the GC-MS. Chromatographic conditions were as follows: the oven was held for 3 min at 40 °C, heated to 250 °C at 5 °C/min, and finally held for 3 min at this temperature. The mass spectrometer was operated in the electron impact mode with a source temperature of 200 °C, an ionizing voltage of 70 eV, and the transfer line temperature was 250 °C. The mass spectrometer scanned masses from 48 to 400 m/z at a rate of 3.41 scan/s.

Peak identification was carried out by comparison of their mass spectra with spectra in the NIST/EPA/NIH Mass Spectral Database (National Institute of Standards and Technology, Gaithersburg, MD, Version 2.0a, 2002, USA), or NIST web book (http://webbook.nist.gov/chemistry/). Ten microliters of 1, 2-dichlorobenzene (0.01ppm in methanol) was used as an internal standard for qualitative identification of the volatile compounds. To confirm the identity of volatile compounds, the retention index (RI) was calculated for each volatile compound using the retention times of a homologous series of C7 to C30 n-alkanes (1000 µg/ml in hexane from Supelco), and comparing

the RI with compounds analyzed under similar conditions (Evrendilek, Tok, Soylu, & Soylu, 2008; Pothakamury, Barbosa-Cánovas, Swanson, & Spence, 1997). The approximate quantities of the volatiles were estimated by comparison of their peak areas with that of the 1, 2-dichlorobenzene internal standard using a response factor of 1.

3.11. Temporal dominance of sensations (TDS)

3.11.1 Ethics statement and location

The Auckland University of Technology Ethics Committee approved the sensory study (AUTEC 13/317) carried out in this research. Panelists gave written and informed consent prior to commencement of the study. Sensory testing took place at the Auckland University of Technology Sensory Suite, Auckland, New Zealand. Sensory sessions were approximately 60 min in duration and as compensation for their time, participants received supermarket vouchers.

3.11.2 Panelist

Ten trained panelists (5 males, 5 females) between 21 and 29 years of age participated in this study. They were recruited online through an advertisement posted on social networking services (i.e., Facebook andWeChat) and were rewarded for their participation. None of the panelists were smokers or suffered from hearing, eating disorders, or other health problems associated with food.

3.11.3 Panel training

Panel training was carried out over three sessions over a total of 12 h of training. Panelists were informed that they would generate sensory attributes associated with lamb meat. The training session consisted of: (1) explanation of the principle of TDS, and the definition of dominance according to Pineau et al. (2009), (2) Reaching inter-agreement between panelists on the relevant sensory attributes of lamb meat as well as their definitions and reference food sample, (3) Familiarization of panel with the

TDS interface using the FIZZ Acquisition Software (Biosystems, Counternon, France), and (4) Running a dummy TDS trial using the agreed sensory attributes.

In the first training session, panelists familiarized themselves with the measurement of sensory sensations of food using the TDS procedure, where the concept and measurement of dominance were introduced. Panelists were trained to familiarize themselves with 'dominant' attributes, defined as "the attribute associated to the sensory sensation of food that captures attention at a given time", and to understand that dominance may change when a new sensation is experienced (Labbe, Schlich, Pineau, Gilbert, & Martin, 2009; Pineau et al., 2009). They were also familiarized with the use of an unstructured 100 mm line scale, anchored with "None" at the left end and with "extreme" at the right end (Pineau et al., 2009). In the second training session, an initial set of 18 relevant sensory attributes was selected that corresponded to described attributes found in red meats as reported in literature (Gasperi, Biasioli, Gallerani, Fasoli, & Piasentier, 2005; Maughan, Tansawat, Cornforth, Ward, & Martini, 2012; St. Angelo, Koohmaraie, Crippen, & Crouse, 1991). Agreement and removal of attributes from the list were discussed until consensus was reached between panelists. Participants were also asked to provide the researcher the reference sample of each attribute chosen. Description of the five selected sensory attributes used in this study is shown in Table 4. The appearance order of sensory attributes was randomized between panelists but maintained for each panelist between samples. A dummy TDS trial was carried out in the third training session. Panelists were instructed to place the cooked meat cube (1 × 1 × 1 cm) that was approximately 5±0.5 g into their mouth. They were then asked to rate their dominant sensations based on the reference attributes agreed in the second training session. This was done to familiarize panels with the TDS interface using the FIZZ software (Biosystemes, Counternon, France).

Table 4 Description of sensory attributes used in the TDS trial

Attribute	Taste definition in lamb	Reference
Initial tenderness	Minimum force necessary (first bite) to bite the meat sample with incisors teeth	3,different cuts of lamb (tederloin,shoulder, leg) sous vide cooked and then grilled to an internal temperature of 70 °C
Meaty	Flavours and aromatics associated with boiled lean lamb meat	Lamb boiled at 100 °C for 10 min.
Browned	Flavours associated with meat that is cooked and charred on the outside.	Lamb cooked at 70 °C, and allowed to brown on each side for 10 min.
Juicy	Amount of water retained in cooked meat that contribute to succulence.	Different cuts of cooked lamb with varying levels of juiciness.
Livery	Taste associated with animal organs.	Lamb liver cooked at 70 °C for 10 min.
Oxidized/ warmed over flavour	Flavour of reheated meat	Cooked lamb that was refrigerated for at least 24 h before reheating.

3.11.4 TDS procedure

TDS procedure was modified from Albert, Salvador, Schlich, & Fiszman (2012). Briefly, TDS measurements were obtained for five sensory attributes (meaty, browned, juicy, livery and oxidized) after initial tenderness was evaluated using a 100 mm unstructured line scale. Each sensory booth was equipped with a computer screen that presented instructions to panelists on how to consume the lamb sample over time. TDS ratings of all samples were obtained using a 100 mm unstructured line scale, with meaty, browned, juicy, livery and oxidized attribites displayed in order at the top corner of the computer screen. Panelists were instructed to continuously report any changes in sensory attributes of the lamb sample during a 80-s period using TDS scales; from the first bite to swallowing and, if present, to after taste sensations. As soon as the panelist clicked on the unstructured line scale of initial tenderness on the computer screen, the panelist was prompted to place the cooked lamb sample into their mouth. On the 30-s mark, the panelist was asked to swallow the sample. The action of clicking on the line scale that appeared on the computer screen activated the software to record TDS ratings every second for up to 80 s. All ratings were

recorded using the FIZZ Acquisition software (FIZZ Network v2.46b, Biosystemes). Detailed instructions were given to standardize consumption behavior. A compulsory 45s break in-between samples were provided to allow panelist to drink and rinse their mouth with filtered water.

In each session, the panelists were presented with 7 samples. A total of 24 sessions (56 samples in triplicates) were carried out. In the TDS methodology, all the attributes were presented simultaneously on the computer screen with their corresponding 100 mm unstructured line scale, anchored at the extremities with "not at all intense" and "very intense". During the evaluation, participants had to select the dominant attribute and scored this attribute on the scale. When the dominant perception changed, the new dominant sensation was scored. The subject was free to choose several times the same attribute or conversely to never select an attribute as dominant. The data collected during the tasting of each product for each subject were the time when an attribute was selected as dominant, attribute name, and attribute intensity scored. A duration parameter was also computed as the time elapsed between the elicitation of the given attribute and the following elicitation.

3.11.5. Tasting condition

The presentation design of the samples utilized a balanced position and order effects, based on the Williams Latin Squares design (MacFie, Bratchell, Greenhoff, & Vallis, 1989). Products were coded with three digit random numbers and the 1 cm_3 cube portion was served at 60 ± 0.5 °C in a 100 ml cup. Rinsing was done between products with water and unsalted crackers during a 60-s break. Sensory testing was conducted in a temperature-controlled room (18 °C), under white light in individual booths.

3.12.Statistical analysis

3.12.1 Questionaire

A frequency distribution analysis of the sample population was carried out according to age, race, gender, income, occupation and education level, and gender. For categorical variables, a chi-squared analysis was utilized (Bovalino, Charleson, & Szoeke, 2016). Independent sample t-tests were employed to compare means of continuous variables. Canonical Variate Analysis (CVA) was conducted to evaluate the differences between lamb cuisines consumed in different regions in China and consumer perception of lamb meat obtained locally in China, and imported from New Zealand, Australia, Uruguay and other countries. CVA was used in this study as it can maximize the distances between products, while minimizing residual variability (Monrozier & Danzart, 2001). Hotelling-Lawley Multivariate Analysis of Variance (MANOVA) tests was carried out to determine if significant differences exist between each product loadings (α=0.05).

3.12.2. Physicochemical Data analysis for HPP and PEF study

HPP

The data were collated using Microsoft Office Excel 2016, and subjected to statistical analysis using the XLSAT MX software release 2016 (Addinsoft, USA). One-way analysis of variance (ANOVA) was carried out on colour, lipid oxidation, fatty acids and free amino acids profiles of processed cuts with the difference considered significant at $p<0.05$. When ANOVA was significant, means were separated by pairwise comparison using the Fisher's least significant difference test. The main effects of processing and cuts, and their interaction were determined using MANOVA at a significance level of $P \leq 0.001$.

PEF

The data were collated using Microsoft Office Excel 2016, and subjected to statistical analysis using the XLSAT MX software release 2016 (Addinsoft,

USA). One-way analysis of variance (ANOVA) was carried out on colour, cooking loss, lipid oxidation,fatty acids, free amino acids and volatile profiles for processing on each cuts with the difference considered significant at $p<0.05$. When the ANOVA was significant, means were separated by pairwise comparison using the Fisher's least significant difference test. The effect of processing and cut and their interaction was tested using a MANOVA for a significance level of $p \leq 0.05$.

3.11.3 TDS

Panel dominance curves for TDS were generated using the FIZZ Calculations software (FIZZ Calculations v2.46b, Biosystemes). The determination of chance and dominance levels on panel curves were carried out using the methods developed by Pineau et al. (2009), and Lenfant, Loret, Pineau, Hartmann, and Martin (2009). Chance level, is the dominance rate that an attribute would obtain by chance. Its value, P_0, is equal to 1/p, where p is the number of attributes. Significance level is the minimum value this proportion should be equal to in order to be significantly higher than P_0. This was calculated using the confidence interval of a binomial proportion based on a normal approximation. Temporal dominance curves depict the proportion of panellist who selected the attribute as dominant at a given time. The higher the dominance rate for the attribute, the better the agreement among panelist.

Canonical Variate Analysis (CVA) of duration and frequency of sensations was conducted with dominance duration as the dependent variable to evaluate the differences between lamb samples based on the sensory attributes as carried out by Jager et al. (2014). In addition, Hotelling-Lawley trace Multivariate Analysis of Variance (MANOVA) tested for significant differences between each product loadings at the 5% level. CVA was used in this study as it can maximize the distances between products, while minimizing residual variability (Monrozier & Danzart, 2001).

Chapter 4. Results and Discussions

4.1. Perception and purchasing behaviors of New Zealand lamb meat by Chinese consumers

China surpassed the United States in 2017-2018 as New Zealand's main red meat importer that accounted for one-third of New Zealand's red meat exports. The continued increase in beef exports has been accompanied by increases in lamb and mutton as well (Beef & Lamb, 2018). The demand for sheepmeat from China, especially mutton, coupled with the limited supply from Australasia, have increased the overall average value of lamb exports. In China, pork is consumed the most (30.3 kg/capita/year), followed by beef (3.9 kg/capita/year), and finally sheep and goat meat (3.1 kg/capita/year) (OECD/FAO, 2018). Although pork is widely consumed in China, meat consumption patterns and attitudes towards meat have changed with China's rapid economic development. With the increased income availability, sheep meat have become more popular in China (Mao et al., 2016). Therefore, it is impotant to understand the factors that influence consumer perception and purchasing behaviour of lamb meat in China in order to to take advantage of the changing consumer and distribution trends in China to gain competitive marketing advantage.

Meat and meat products represent an important source of protein in human diets, and their quality varies according to intrinsic (e.g. percentage of fat, colour) and extrinsic (e.g. origin or production, price, quality labels) factors that can be used to make a product more desirable (Bernabéu, Rabadán, El Orche, & Díaz, 2018; Maria Font-i-Furnols & Guerrero, 2014). Font-i-Furnols & Guerrero, (2014) further summarized the intrinsic and extrinsic factors into psychological (individual factor), sensory (product-specific factor) and marketing (environmental factor) types, which affect consumer behaviour and preferences for meat and meat products.

Consumer experiences, acquired knowledge and personal characteristics of consumers determine consumer attitudes, buying intentions and preferences (Maria Font-i-Furnols & Guerrero, 2014). In general, consumers consider meat to be a healthy and important component of the diet. Consumer demand in relation to food is shifting towards products that are safe, nutritious and good quality (Verbeke et al., 2010). "Quality" and "healthfulness" are reported to be one of the most important factors for influencing consumers' choice for foods.

Chinese consumers are also concerned about meat safety. Li (2012) and Zhang (2014) found that most Chinese consumers evaluated sfaety of meat based on color and appearance of freshness of beef and sheep meat. Colour is an important fresh meat characteristics at the point of purchase (Gracia & de-Magistris, 2013). Bernués, Ripoll, & Panea (2012) characterised profiles of lamb meat consumers in Aragon, Spain. They found that fresh appearance and light colour of meat were valued by traditional consumers. Since meat is considered a potentially harmful product for health, correct labelling is a key factor for consumers (Bernués, Olaizola, & Corcoran, 2003). Schleenbecker & Hamm (2013) concluded that consumers are confident in governmental institutions that are responsible for certification, and placed more trust in certified labeling. Chinese consumers will pay up to 10% more, if the meat is labelled as "green or organic" (Mao et al., 2016).

The effects of country of origin on consumer preference of meat have been widely studied. Font-i-Furnols et al (2011) investigated consumer's purchasing decisions for lamb meat in three European countries: Spain, France and United Kingdom. In addition, four countries were considered for evaluating the effect of country of origin (local, Argentina, Switzerland and Uruguay). Country of meat origin had a great influence in purchasing intention, with local meat the most preferred and Uruguayan lamb the least preferred. Hersleth, Næs, Rødbotten, Lind, & Monteleone (2012) further showed that country of origin also influenced consumers' purchasing decisions of lamb meat in Norway and Italy, with domestic meat preferred

in both countries. However, little is known on how country of origin affects Chinese consumer preferences. Differences in consumer preference of meat have been found in different regions on mainland China.

Consumers not only expect meat products in the market to be of adequate nutritional value, but also they prefer meat to be wholesome, fresh, lean, and with adequate juiciness, flavour and tenderness (Dransfield, 2001, 2003; Ngapo & Dransfield, 2006). Tenderness, sheep meat flavour, overall liking and cooking odour are important eating attributes of sheep meat (Pethick et al., 2005; Pleasants et al., 2005). According to Dransfiel (2001), tenderness is the primary determinant of acceptability and eating quality of meat. Meat tenderness is a very complex characteristic of the meat quality, as it is biologically dependent on the factors such as species, age, fat code, gender, retail cut chosen, method of cooking, and muscle type (Dransfield, 2001).

Liu (2012) reported that Chinese consumers based purchasing decisions of red meat on flavour (24.8%), nutritional value (18.8%) and ease of cooking (12.4%). Li (2006) found that Chinese consumers eat beef because of its flavour (41.8%), consumer dietary habits (30.9%) and nutritional composition (18.2%). In contrast, 57.3% Chinese do not like sheep meat because of off-flavour (Zhang, Sun & Feng, 2014). Cooking methods, as one of five components of food-related lifestyle, ultimately impacts the consumer purchasing behaviour of meat (Grunert, 2006). Zhang (2014) found that 54.68 % of Chinese consumers stewed sheep meat, 29.2% cooked lamb in a hot pot, and 16.2% roasted sheep meat.

As the red meat sector in New Zealand continues to fluorish from its exports into China, it is increasingly important to differentiate meat products in the Chinese market to pursue continued export volume growth. Understanding the attributes that Chinese consumers associate with in terms of quality, safety and production in a natural environment will help provide opportunities for increasing export returns. Hence, the aim of this study was to investigate factors that influence consumer perception and purchasing

behaviour of lamb meat in China in order to enhance sheepmeat exports to China.

4.1.1. Consumer characteristics

The survey generated a total of 601 valid questionnaires. Table 5 shows the demographics of consumers by gender, age, job category and educational background. Female respondents accounted for 56.7% (337) of the participants, whereas 43.93% (264) were males. In terms of age group distribution, 44.59 % of respondents were between 21 and 30 years of age, and 34.61% of consumers were between 31 to 40 years. The majority of respondents were married (68.23%). A large proportion of the participants (82.36%) lived in a three-person household, with only a small proportion (3.83%) who lived alone. Most of the participants who completed the questionnaires stated their occupations as: manager (14.64 %), full-time students (12.98 %), and working in the field of technology research and development (12.81 %). In terms of annual income distribution, 26.79% respondents had a high annual income of more than 100,000 yuan, followed by 26.46% respondents with a medium-high income (50-90k yuan).

The majority (79.2%) of respondents in this study had higher education level, with 58.40 % having a Bachelors degree, and 20.47 % and 15.14% having postgraduate and diploma qualifications respectively. 55.57% of the respondents resided in East China (mainly Shanghai and Jiangsu), and 29.28% in North China (mainly Beijing). More than half of overall respondents are from southern China (64.23%).

Table 5 Socio-demographics of Chinese consumers (n = 601)

Variable	Categories	Frequencies	%
Gender	Male	264	43.93%
	Female	337	56.07%
Age	Under 20	9	1.50%
	21-30	268	44.59%
	31-40	208	34.61%
	41-50	83	13.81%
	51-60	26	4.33%
	Above 60	7	1.16%
Marital	Single	124	20.63%
	In a relationship	79	13.14%
	Married	386	64.23%
	Others	12	2.00%
Occupation	Full time student	78	12.98%
	Production workers	21	3.49%
	Salesman	27	4.49%
	Market/Public Relations Officer	14	2.33%
	Customer Service Staff	10	1.66%
	Admin/Support Staff	51	8.49%
	Human Resource Staff	21	3.49%
	Financial Audit Staff	44	7.32%
	Civil servant	46	7.65%
	Technical R&D	77	12.81%
	Manager	88	14.64%
	Teacher	29	4.83%
	Adviser	5	0.83%
	Professional	29	4.83%
	Others	61	10.15%
Annual salary (yuan)	Under 4.9k	50	8.32%
	5-14k	91	15.14%
	15-49k	80	13.31%
	50-99k	159	26.46%
	More than 100k	161	26.79%
	No income	60	9.98%
Education	Primary	1	0.17%
	Junior	6	1.00%
	Secondary	27	4.49%
	Diploma	91	15.14%
	Bachelor	351	58.40%
	Postgraduate	123	20.47%
	Others	2	0.33%
Household size	1 people	23	3.83%
	2 people	83	13.81%
	More than 3 people	495	82.36%
Resident	North China	176	29.28%
	Northeast China	31	5.16%
	East China	334	55.57%
	South Central China	36	5.99%
	Southwest China	15	2.50%
	Northwest China	8	1.33%

4.1.2. Consumer perception of lamb meat in China

Consumer experience

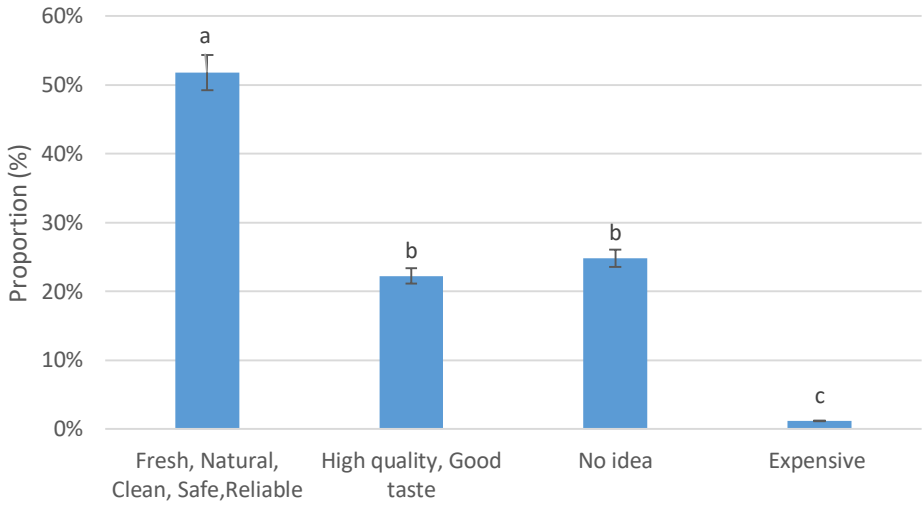

Figure 16 Chinese consumers responses towards the perception of New Zealand food products

To gain an overall impression of New Zealand meat and meat products, participants were asked to come up with words or phrases that best described New Zealand food products (Figure 16). 51.80% of the Chinese consumers perceived New Zealand food products as being safe and produced under good environmental conditions, which is related to words like green, clean, natural, safe and relaiable. The New Zealand Food Safety Authority established strict food legislation and standards to monitor the safety of food products sold and manufactured for export to the overseas market (Gruber, Brooke-Taylor, Goodchap & McCullum, 2003). People also associated New Zealand meat products as being clean and green. As a country, New Zealand cultivates a “clean green” image and the perceptions about lifestyle and values implied by this image, especially in marketing the country as a tourist destination (Coyle & Fairweather, 2005). These promotional efforts had a strong, positive carry-over effect for New Zealand’s agricultural products and meat industry (Clemens & Babcock, 2004).

Table 6 Chinese Consumer perception of lamb meat

	Variable	Categories	Frequencies	%
Experience	Preference of species	Beef	196	32.67% (a)
		Pork	87	14.46% (c)
		Lamb	143	23.72% (b)
		Mutton	116	19.33% (b)
		All	59	9.83% (d)
	Factors influencing preference	Good taste	489	33.56% (b)
		Nutritious and healthy	665	45.64% (a)
		Cheap price	58	3.98% (d)
		Meat consumer	169	11.6% (c)
		Easy to purchase	68	4.67% (d)
		Others	8	0.55% €
	Perceived healthier	Pork	41	6.82% (c)
		Beef	287	47.75% (b)
		Lamb	225	37.44% (a)
		Mutton	48	7.99% (c)
	Perceived high cholesterol	Pork	372	61.90% (a)
		Beef	39	6.49% (c)
		Lamb	42	6.99% (c)
		Mutton	40	6.66% (c)
		I don't know	100	16.64% (b)
		I don't know what the cholesterol is	7	1.16% (d)
	Reason people don't like lamb/ mutton	Cheap	3	1.69%
		Fresh Colour	37	20.79%(c)
		High Fat	2	1.12%(e)
		Juicy	6	3.37%(e)
		No-off flavour	62	34.83%(a)
		Nutritive	15	8.43%(d)
		Organic	1	0.56%(f)
		Promotion	4	2.25%(e)
		Tender	48	26.97% (b)
	Lamb consumer	Yes	492	81.86%(a)
		No	109	18.14%(b)
	Why do you prefer lamb than mutton	Fresh & tender in texture	454	38.74%(a)
		No odour	185	15.78%(c)
		Healthier	396	33.79%(b)
		More juicy	132	11.26%(d)
		Other	5	0.43%(e)
	Cooking method	Pan fried	212	17.15%(b)
		Oven-broiled	99	8.01%(c)
		Boiled	128	10.36%(c)
		Barbecued	198	16.02%(b)
		Stew	215	17.39%(b)
		Steam	47	3.8%(d)
		Hot pot	329	26.62%(a)
		Other	8	0.65%(e)

Continued Table 6

	Variable	Categories	Frequencies	%
Eating habit	offal	Yes	287	58.33%(a)
		No	205	41.67%(b)
	Frequency	Not often	169	34.35%(a)
		Once a month	176	35.77%(a)
		Once a week	117	23.78%(b)
		1-3 times in a week	27	5.49%(c)
		4 or 5 times in a week	3	0.61%(d)
	Occasion	Home	246	37.27%(a)
		Restaurant	173	26.21%(b)
		Night market	10	1.52%(f)
		Wedding	43	6.52%(e)
		Business meeting	65	9.85%(d)
		Festival	112	16.97%(c)
		Others	11	1.67%(f)

a,b,c,d,e,f means with different letters in same categorical variable show the significant dif difference ($p<0.05$) using chi-squared test.

As seen in Table 6, results demonstrated that beef was the major red meat consumed (32.67%), followed by lamb (23.72%), mutton (19.33%) and pork (14.46%) . Although pork was traditionally consumed in the largest amount in China, increased consumption levels of beef and sheep meat (lamb and mutton) were found in this study. Font-i-Furnols & Guerrero (2014) also reported that consumers from Spain, France and United Kingdom considered pork as being less healthy and much fattier than beef and poultry. Making low-fat choices were associated with consumption of smaller amounts of pork and processed pork products in the United States (Guenther, Jensen, Batres-Marquez, & Chen, 2005). In this study, almost half of the consumers believed that the main factor that influenced purchase of meat was its nutritious and healthy characteristics (45.64%), followed by quality (33.56%). Li (2006) reported that Chinese consumers ate beef because of its flavour (41.8%), eating behaviour (i.e. occasion, religious beliefs and seasonality) (30.9%), and nutrition (18.2%). Consumers also made decisions about meat purchase based on dietary habits, flavour, nutritional value and ease of cooking (Mao et al., 2016). In addition, 47.75%

and 37.44% of consumers believed that consuming beef and sheep meat respectively were much healthier options than mutton and pork. 61.9 % of consumers believed that consuming pork had high cholesterol.The popularity of lamb meat has been attributed to its nutritional value, flavour, diversification in the type of meat consumed, cultural eating habits (religious beliefs and regional differences) and safety (Ding, 2014).

This study demonstrated that consumers did not like eating sheep meat (lamb and mutton) due to off-flavor (34.83%), and lack of tenderness (26.97%) and fresh colour (20.79%) (Table 6). Consumers have been reported to find sheep meat unacceptable due to odour/flavor (Prescott, Young, & O'Neill, 2001). There is also low consumption of sheep meat in many Asian countries due to sheep meat odour, especially during cooking, and its flavour when eating (Erasmus, Muller, & Hoffman, 2017). Chinese consumers describe the cooking odour of sheep meat by using the hedonically negative word "soo", which means sweaty or sour (Wong, Johnson, & Nixon, 1975).

A total of 492 out of 601 (81.86%) consumers have eaten lamb (Table 6). In terms of sensory preference, 38.74% of Chinese consumers preferred lamb than mutton, because of the fresh and tender texture attributes. Lamb meat is more tender as it is obtained from young sheep, while mutton which is not as tender is obtained from older sheep. Young & Braggins (1993) examined the eating quality of the M. semimembranosus from sheep aged from 4 months to 5 years. They found that eating quality decreased as animals became older. This was due to an increase in collagen concentration, more than a decrease in collagen solubility that was attributed to the highly insoluble nature of collagen in the muscle. In addition, 33.79% Chinese consumers considered lamb to be more healthier than mutton. Hopkins & Mortimer (2014) reviewed the effect of genotype, gender and age on sheep meat quality and concluded that higher concentrations of muscle lipid was found in older (43 weeks) lamb than younger lamb (16 weeks). As dietary fats may

increase cholesterol and lead to heart diseases, consumers believed that lamb meat was a healthier option than mutton meat.

Sheep meat was mainly consumed by Chinese consumers in a hotpot meal (26.62%). In a hotpot meal, strips of meat (primarily rib and flap cuts and trim) are dipped in pots of boiling water for ten seconds (Manton-Pearce, 2013). The next most common method of consuming lamb was by stewing (17.39 %), which was not significantly different to pan-fried (17.15%) and barbecued (16.02%) methods. Stewing utilises tougher and inexpensive meat cuts, like chunk, shoulder, rib and shank cuts. Pan frying is a fast cooking method that uses a small quantity of hot fat (oil and butter), and typically high heat and shorter cook times. Hence, high-value meat cuts like ribeye, sirloin and tenderloin are used for pan-frying. On the other hand, barbecuing involves a longer period of cooking time with indirect heat (wood chips and logs), and meat cuts that are usually used are rump, brisket and shoulder meat cuts. Zhang (2014) reported that Chinese consumers mainly consumed stewed sheep (54.68%), followed by hot pot (29.2%) and roasted (16.12%) sheep meat. The different methods of cooking meat in fact utilises meat cuts of different quality. Hence it is not necessarily high value prime cuts like the loins and legs that Chinese consumers require. Thus there is a great potential to market low value cuts of lamb meat for the Chinese market.

Eating habit

Over half of the consumers (58.33%) also indicated that they eat offal (Table 6). Major cities, such as Guangdong, Shanghai, Liaoning, Jiangsu and Henan, were mainly offal import cities in China, and since 1995 have imported offal from the USA, Canada and Denmark (Wang, Fuller, Hayes, & Halbrendt, 1998). According to Oh & See (2012), while Western consumers like lean meat, the Chinese consumers like more fat-containing pork offal. Chinese consumers have been reported to pay high prices in the premium market segment for imported beef and beef offal from pastoral countries, such as

Australia, as they perceive cattle raised on grasslands produces chemical-free beef meat (Brown, Longworth, & Waldron, 2002).

About 35.77 % of consumers ate lamb at least once a month in this study (Table 6). Lamb was consumed either at home (37.27%), restaurant (26.21%), festivals (16.97 %), business meetings (9.85%) and weddings (6.52%). Chinese families usually consume red meat daily (Liu, Parton, Zhou, & Cox, 2009). Eating meat outside is becoming more common. Ding (2014) reported that 48%, 36% and 47% urban residents living in eastern, central and western regions of China respectively consumed sheep meat outside home.

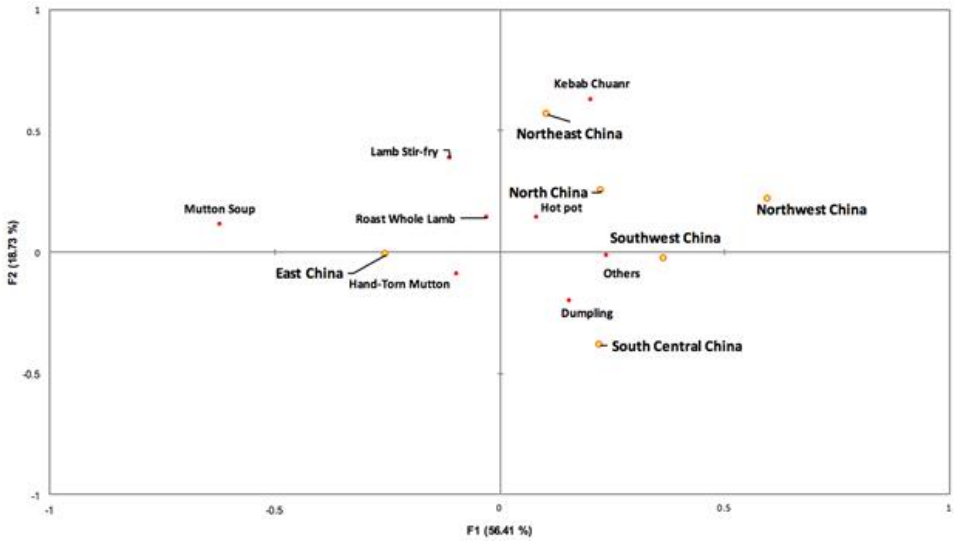

Figure 17 CVA Biplot summarizing the different lamb regional cuisines in China

A CVA plot of the regional lamb cuisines in China is shown in Fig 17 that described 56.41% and 18.73% of the total variation of factor 1 (F1) and factor 2 (F2), respectively. It is clear that lamb cuisines varied with the different regions of China. East China cuisines had negative scores, which corresponded to hand-torn mutton, roast whole lamb, lamb stir-fry and mutton soup, while the rest of cuisines from other regions had positive scores along F1 . In general the northern and southern region cuisines were separated along F2 that explained 18.73% of the variance. Southwest and South-central China cuisines had negative scores that corresponded to dumpling , while Northeast, Northwest and North China cuisines had

positive scores that corresponded to Hotpot and Kebab (Chuanr) along F2. China consists of 56 ethnic groups that have different food culture. Liu (2011) reported that the different cuisines between northern and southern regions can be attributed to the different climate and geography. For example, Northern China is cold in winter, requiring food high in calories to provide sufficient energy to tolerate the cold. Zhu et al (2013) also found that geographical location is an important factor that determine cuisines in the different regions. In North China (include Northeast, Northwest China), there are more sheep and the people of Mongol ethnic origin typically consume lamb and mutton with typical lamb dishes like Hotpot and Kebab (Chuanr) (Simoons, 2014). East China lamb cuisines on the other hand are dominated by broths, soup-like dishes, and stews which is supported by findings in this study that found mutton soup to be correlated mutton soup to this region. In south central China, “swallow skin” (wonton or dumpling) is a popular cuisine. It comprise a thin dough that contain meat, and can be steamed or added to soups (Simoons, 2014).

4.1.3. Consumer purchasing behaviour of lamb meat in China

Table 7 Chinese Consumer purchasing behaviour of lamb meat

	Variable	Categories	Frequencies	%
Purchase drivers	Factors influencing on purchasing	Species	56	9.32% (c)
		Freshness	384	63.89% (a)
		Low fat	27	4.49% (d)
		Price	30	4.99% (d)
		Healthiness	86	14.31% (b)
		Country of origin	16	2.66% (e)
		Others	2	0.33% (f)
	Price	40-100 yuan /kg	166	33.74%(a)
		101-120 yuan /kg	145	29.47%(b)
		121-140 yuan /kg	90	18.29%(c)
		141-160 yuan /kg	45	9.15%(d)
		161-200 yuan /kg	31	6.3%(de)
		Others	15	3.05%(e)
	Prefer price same	Mutton	39	7.93%(b)
		Lamb	453	92.07%(a)
	Sensory attributes	Colour	252	28.35%(b)
		Tenderness	362	40.72%(a)
		Juiciness	80	9.00%(d)
		Flavour	184	20.7%(c)
		Others	11	1.24%(e)
	Country of origin	Local	110	18.30% (b)
		Imported	207	34.44% (a)
		I don't mind any meat	284	47.25% (a)
	Purchase drivers for Imported meat	High quality taste and texture	439	28.43% (a)
		Food safety	397	25.71% (a)
		Packaging	47	3.04% (d)
		Nutrition	228	14.77% (b)
		Fashion	28	1.81% (de)
		Price	212	13.73% (bc)
		Advertisement	31	2.01% (de)
		Convenience	154	9.97% (c)
		Others	8	0.52% (e)

Continued Table 7

Variable	Categories	Frequencies	%
Purchase location	Chinese islamic market(halal)	41	8.33%(c)
	Farm market	142	28.86%(a)
	Convenience store	12	2.44%(d)
	Butchery	59	11.99%(c)
	Online shopping	80	16.26%(b)
	Others	6	1.22%(d)
	Supermarket	152	30.89%(a)
Seasonality	Spring	122	24.8%(b)
	Summer	37	7.52%(d)
	Autumn	73	14.84%(c)
	Winter	260	52.85%(a)

a,b,c,d,e,f means with different letters in same categorical variable show the significant dif difference ($p<0.05$) using chi-squared test.

Purchase drivers

Consumers believed that freshness (63.89%) was an important factor when purchasing red meat, followed by healthiness (14.31%) (Table 7). Freshness as assessed by consumers not only predict eating quality but also indicate safety. Ding (2014) noted that 95.6% of urban residents and 88.1% of rural residents were concerned about meat freshness in China. Healthiness is also a common reason for changing consumption habits. In general, consumers tend to consider meat to be a healthy and important component of the diet (Verbeke et al., 2010) that provide nutritious elements like proteins and vitamins.

The key drivers that influence the purchase and "willingness to pay" decisions when buying sheep meat is leanness, palatability, and good nutrition (Pethick, Banks, Hales, & Ross, 2006). About 63.21 % of consumers think that the price of lamb meat between 40 and 120 yuan/kg was acceptable (table 7). According to Mao et al (2016), the average price of sheep meat was between 46.1 yuan/kg to 78.6 yuan/kg in 2013-2014, which is much lower than 100 yuan/kg consumers are prepared to pay for. This might be due to the fact that consumers believed in either paying a higher price to get good quality meat (Becker, Benner, & Glitsch, 2000) or consuming high-quality and safe meat with increased income (Yu, Gao, &

Zeng, 2014). In this study, 92.07% of consumers indicated preference to buy lamb if mutton and lamb were similar in price. Obviously, consumers would like to pay less money to get more delicate taste with desirable flavour lamb meat than mutton.

The most important attributes when purchasing lamb by consumers were identified to be tenderness (40.72%), color (28.35%) and flavor (20.7%) in this study (Table 7). The eating quality attributes, tenderness and juiciness, have been shown to positively influence consumers' preference of beef (Polkinghorne & Thompson, 2010), pork (Aaslyng et al., 2007) and lamb (Font-i-Furnols et al., 2011). Tenderness is considered a significant attribute of lamb texture (Beef & Lamb, 2018). Tenderness are highly correlated with the overall experienced quality, intention to purchase and willingness to pay (Banović et al., 2009, Bello Acebrón and Calvo Dopico, 2000, Lusk et al., 2001). Color has been reported to be one of the most important fresh meat characteristics at the point of purchase (Gracia & de Magistris, 2013; Ngapo, Martin, & Dransfield, 2007; Verbeke et al., 2005), probably because consumers use inadequate color as an indicator of spoilage and wholesomeness (Mancini, 2009). Flavour was another attribute of lamb that influenced consumer, (Hoffman et al., 2005). Different from beef and pork, lamb has a stronger flavour and lower palatability (Rhee & Ziprin, 1996). A survey of mutton consumption habit and buying behavior in urban and rural area of China by Zhang (2014) showed that 41.7% Chinese consumers like the flavour of sheep meat.

In this study, 34.44% consumers preferred ($p<0.05$) imported meat than local meat (18.3%) (Table 7). Many Chinese consumers prefer to buy imported rather than locally produced meat due to safety, quality, and health factors (Henchion et al., 2014). Knowledge and attitudes about meat products may influence consumer preference (Guenther, Jensen, Batres-Marquez, & Chen, 2005). Since the melamine-contaminated milk scandal happened in 2008, food safety incidents in China have received considerable attention (Knight et al., 2008). Consumers believe that export countries

establish regulations and food security standards that are stricter and more rigorous, giving imported food products a better reputation (Font-i-Furnols et al., 2011). As local Chinese meat producers are unable to meet the needs of their consumers, this has resulted in increased consumption of imported lamb meat.

47.25% of the participants in this study believed that local and imported meat have attributes of high quality (28.43%) and good food safety (25.71%). Consumers consider the price (13.73%) and packaging of product (3.04 %) when making decisions (Table 7). Hoffman, Muller, Schutte, Calitz, & Crafford (2005) concluded that the purchasing behavior of consumers is dependent on the quality, price and promotion of product. Price of product is considered as the most significant variable when making purchasing decisions by consumers (Bernués, Ripoll, & Panea, 2012). However, consumer preferred food products that are safe, nutritious and high quality (Trindade et al., 2011; Verbeke et al., 2010).

Purchase location

Consumers believed that meat directly purchased from the farm and supermarket is fresh (Bond, Thilmany, & Bond, 2009). In this study, 30.89% and 28.86% of consumers' purchased lamb at supermarket and farm market, respectively (table 7). Consumers feel confident about the food being safe when buying food from the supermarket (Burch, Dixon, & Lawrence, 2013). Although China is the world's largest Internet market, with Chinese users spending more time on the internet than United States users (Clemes, Gan, & Zhang, 2014), only 16.26% consumer preferred to purchase meat online. According to Chen, Yan, & Fan (2015), safety is the greatest consumer concern that strongly influenced online purchase.

Seasonality

According to traditional Chinese medicine, sheep meat is thought to promote body warmth. Therefore, Chinese believed that consumption of sheep meat in cold weather was good for health. Icn fact, onsumption of

lamb is 'recommended' by Chinese doctors in winter and autumn only. This is supported by results in this study that showed 52.85% of consumers preferring to consume lamb in the winter, followed by spring (24.80%), autumn (14.84%) and summer (7.52%) respectively (Table 7). A study by Ding et al. (2013) also reported that sheep meat consumers who had seasonal preference preferred to eat this meat in the winter (57.07%), while 13.07%, 5.16% and 18.87% of the consumers preferred to eat meat in autumn, spring, and summer respectively.

Safe food labels in China

Table 8 Safe food labels used in this study

Label	Title of label	Qualifications	Frequencies	%
	Organic food	General Administration of Quality Supervision, Inspection and Quarantine of PRC (AQSIQ)	235	39.05%(a)
	Harmless agricultural product	The Center for Agri-food Quality and Safety, Ministry of Agriculture of PRC	72	12.05%(c)
	Green food	China Green Food Development Center, Ministry of Agriculture of PRC	66	10.99%(c)
	Organic food	China Organic Food Certification Center (OFCC), Ministry of Agriculture of PRC	140	23.31%(b)
	Organic food	China Organic Food Development Center (OFDC), Ministry of Environmental Protection of PRC	74	12.31%(c)
Others		-	14	2.29%(d)

The first three labels are national labels, while the last two labels are marks of the certificate authority. There remain other similar certificate authorities that promote their own labels under national labels.
a,b,c,d means with different letters in same categorical variable show the significant dif difference ($p<0.05$) using chi-squared test.

Consumers often read food labels to obtain information on nutritional value and ingredients that influences food purchase (Larsson, Lissner, & Wilhelmsen, 1999). Rimal (2005) found that meat consumers tended to consume more or less of meat products depending on information stated on packaging labels. With improved living standards, Chinese consumers are increasingly concerned about food quality and safety (Liu, Pieniak, & Verbeke, 2013). The availability of safety related information such as expiry date, origin, and green or organic labels significantly affected the purchase intention of consumers when purchasing meat (Zhou et al., 2004). In this study, 39.05% of respondents chose the certification of organic product from Inspection and Quarantine of PRC (AQSIQ), while 23.31% of respondents preferred the general certification of organic product from the China Organic Food Certification Center (OFCC), Ministry of Agriculture of PRC (Table 8). It can be concluded that Chinese consumers prefer products with organic certification labels, and trusted national labels more than certificate authority labels. This because of the majority of Chinese consumers consider the government to be the most trustworthy source of information, followed by specialized institutions and the mass media (Liu et al., 2013). With increased concern about food safety and the environment, the Chinese government have established a range of certification projects. The criteria for organic food are the strictest, followed by those for green food and hazard free food (Gao & Zhang, 2002). The three categories of safe food labels, such as organic food, harmless agricultural product, and green food as shown in Table 8 have been considered as safe food (Wang & Wei, 2006; Zhou, 2004; Zhou, 2005; Zhou, Huo, & Peng, 2004).

Country of origin

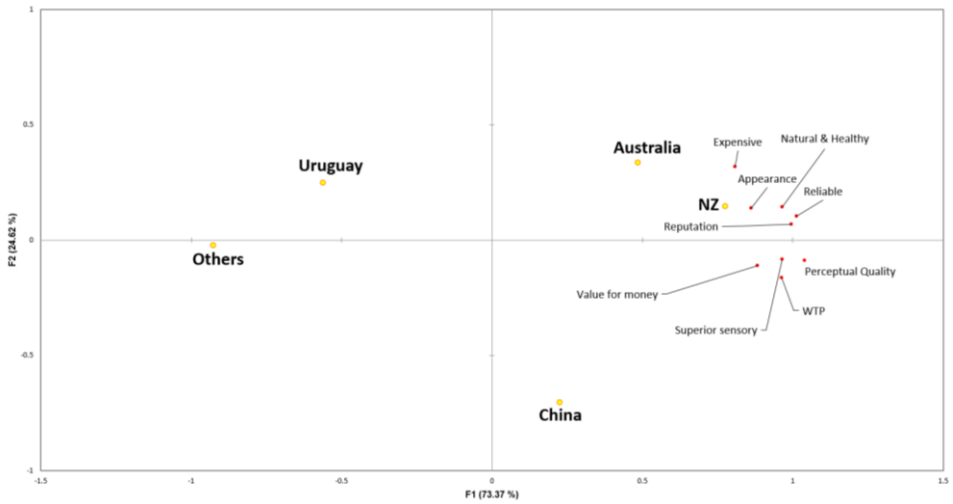

Figure 18 Canonical Variate Analysis Biplot of Chinese consumer perception of local and imported lamb meat

This study also investigated consumer perception of lamb meat from other countries (New Zealand, Australia and Uruguay) and China (Xinjiang, Mongolia). The CVA plot of Chinese consumer perception of local and imported lamb meat is summarized in Figure 18 that described 73.37% and 24.62% of the total variation along factor 1 (F1) and factor 2 (F2), respectively. Meat from Australia and New Zealand had positive scores along F1, which corresponded to expensive, reputation, reliable, appearance, and natural and healthy attributes. China also had positive scores that corresponded to value for money, superior sensory and perceptual quality, and willingness to purchase (WTP).

Consumers generally prefer local meat products (Font-i-Furnols et al., 2011; Schnettler, Ruiz, Sepúlveda, & Sepúlveda, 2008). Consumers in Chile preferred domestic meat as imported meat from Brazil was associated with poorer quality and were perceived less safe (Schnettler et al., 2008). Font-i-Furnols et al (2011) investigated purchasing intention of consumers in Spain, France and United Kingdom (UK) for lamb meat. Most of the consumers preferred meat from their own country. Consumers from UK and France preferred lamb meat from Switzerland the next most. This was attributed to the meat being perceived as fresher or safer due to the proximity of

Switzerland to France and UK. In this study, it was clear that Chinese consumers preferred imported meat from New Zealand because of its reputation, reliable, natural and healthy attributes. Chinese consumers have been reported to buy imported pork rather than locally produced pork as safety, quality, and health factors were deemed important (X. Q. Ma, Verkuil, Reinbach, & Meinert, 2017).

4.1.4. Conclusion

Chinese consumer perception and purchasing behavior of meat were investigated. Chinese consumers perceived beef and lamb to be nutritious and healthy and preferred these red meats over pork. Freshness, flavour, texture, safety and nutrition influenced purchasing behaviour of meat. Chinese consumers are willing to pay more money to purchase imported lamb meat, because they believed it to be high quality in terms of taste, texture and safety. Interestingly, almost 60 % of Chinese consumers consumed offal, which offered a potential opportunity to turn by-products of the meat industry into a valuable commodity. Chinese consumers cooked a variety of lamb meat cuts using different methods like hotpot, pan frying, stewing and barbecuing. Hence it is important that the meat industry establish clear market targets for Chinese consumers in terms of quality requirements, type of meat cuts, regional markets and season when meat is consumed.

4.2. The impact of high-pressure processing (HPP) on physicochemical properties and sensory characteristics of three lamb meat cuts

Consumer demand is increasing for products that are fresh tasting, additive-free, microbiologically safe, convenient to use and shelf stable. Raso & Barbosa-Cánovas (2003) identified that an ideal processing method should be able to inactivate spoilage and pathogenic microorganisms, reduce degradation of organoleptic and nutritional properties, and produce an acceptable product for consumers and regulatory agencies. Many processing methods do not meet all these criteria. Although chilling and freezing can maintain to a certain degree the freshness of food, microorganisms growth are only delayed or inhibited. Thermal processing on the other hand, can inactivate microorganisms and enzymes resulting in safer and more stable products but can adversely affect the organoleptic qualities of the final product such as appearance, taste and flavour as well as its nutritional value (Wilson et al., 2008). Nowadays, newly developed food technologies usually focus on preservation of food while retaining food quality attributes.

High pressure processing (HPP) is an industrially tested technology that offers a more natural, environmentally friendly alternative for shelf life extension of a wide range of food products (Welti-Chanes et al., 2005). The effects of high pressure on microorganisms and proteins were observed to be similar to that of high temperature. Although it is considered a "mild-technology," the use of HPP in high-fat foods causes a significant increase in oxidative processes. Pressure treatment was found to induce lipid oxidation in food products like minced beef (Rivas-Cañedo et al., 2009), ham (Clariana & García-Regueiro, 2011), turkey thigh muscles (Tuboly et al., 2003), and chicken breast muscles (Wiggers, Kröger-Ohlsen, & Skibsted, 2004). The use of HPP with meat has been limited because the pressures and temperatures required to tenderise post-rigor meat denature myoglobin, which subsequently leads to an unacceptable meat colour (Ma & Ledward, 2013).

Studies have reported that HPP pressurization of meat can result in significant colour changes in fresh meat colour of chicken breast fillet (Rodríguez-Calleja et al., 2012), beef (McArdle, Marcos, Kerry, & Mullen, 2010), pork (Souza et al., 2011) and lamb (McArdle, Marcos, Mullen, & Kerry, 2013).

Lipid oxidation consists of a series of chemical and biochemical reactions which cause changes in the type and concentration of molecular species present in a food (Akoh & Min, 2008). Certain physicochemical characteristics of oxidation products can alter the flavour and nutritional quality of foods and produce toxic compounds (Medina-Meza et al., 2014). With lipid oxidation induced by HPP, some changes in individual fatty acids may occur. McArdle et al (2010) reported that high pressure had no effect on polyunsaturated/saturated fatty acid (PUFA/SFA) or omega 6/omega 3 (n6/n3) ratio of beef (M. pectoralis profundus) muscle, but had a significant effect on the sum of saturated (SFA), monounsaturated (MUFA) and polyunsaturated (PUFA) fatty acids. In contrast, the PUFA/SFA ratios of pressurized lamb (*M. pectoralis profundis*) muscles were significantly higher compared to control samples, but without significant effects on omega 6/omega 3 (n6/n3) ratios.

HPP can also modulate the proteolytic activities of meat to improve its quality. Ohmori et al (1991) reported that the free amino acids content of beef rounds significantly increased when meat was treated at 100-400 MPa compared to control samples. However, another research established no significant differences in the amino acids and peptide content of beef (Suzuki et al., 1994) with HPP treatment and concluded that HPP had no adverse effect on the brothy, meaty and cooked flavours of meat. HPP was however found to influence the flavour, juiciness and aroma of chicken breast fillet. Kruk et al (2011) reported that treatment at 300 MPa significantly reduced flavour, aroma and juiciness, with 450 MPa treatment resulting in the weakest aroma. On the other hand, Rodríguez-Calleja et al (2012) demonstrated that pressurized chicken breast fillet at 300 MPa for 5 min

were more acceptable, and had more chicken aroma attribute compared to control. Morton et al (2017) recently demonstrated that beef (*M. longissimus thoracis*) treated at 175 MPa did not influence the juiciness and flavour of meat but significantly improved the overall acceptability and eating scores. However, there are limited studies reporting on the sensory attributes of meat treated with HPP.

Sensory characteristics like appearance, texture, juiciness, and flavour, influence consumers' perceived quality and acceptability of meat products. Temporal Dominance of Sensations (TDS) has only been used in two studies to determine changes in sensory perception of meat. Devezeaux de Lavergne, Derks, Ketel, de Wijk, & Stieger (2015) used TDS to determine the dynamic texture perception of sausages. Results showed that differences in eating behaviour between subjects can change bolus properties of sausages resulting in differences in dynamic texture perception of the same sausage. In another research, TDS and time-intensity (TI) were used to investigate the influence of salt content on the flavour of dry-cured ham (Lorido et al., 2016). The results showed that salt reduction did not have a marked effect on TI analysis for most of attributes between normal salt and reduced salt dry-cured ham. However, TDS curves demonstrated some differences in terms of hardness and fibrousness that had a significantly ($p< 0.05$) higher % standard duration (SD) in normal salt samples compared to reduced salt, while cured flavour had a significantly higher % SD ($p< 0.01$) in reduced salt samples compared to normal samples.

It is evident from previous studies that HPP can influence the physicochemical properties of meat, These changes will in turn affect flavour properties of meat. Hence, the objective of this study was to evaluate the effect of HPP treatment on three different lamb meat cuts (shank, loin and shoulder) in terms of colour, lipid oxidation, fatty acids, free amino acids and temporal sensory changes using the TDS methodology.

4.2.1. Changes in colour

Table 9 The L*, a*, b* and lipid oxidation values of four different lamb cuts with and without HPP treatments at 200, 300, 400 and 600 MPa (mg/100 g dry meat)

Measurements		Cuts	Treatment					Significant of effect[e]		
			C	200	300	400	600	Cut	Treatment	Cut*Treatment
Colour	L	Shank	41.25d	46.845c	53.455b	57.457a	59.258a	ns	***	***
		Loin	39.258d	44.745c	51.581b	55.368a	57.254a			
		Shoulder	40.465d	45.465c	52.165b	56.267a	58.236a			
	a	Shank	6.845a	6.235by	6.325by	6.025b	5.212c	**	***	***
		Loin	7.258a	7.185ax	6.857bx	5.925c	5.845c			
		Shoulder	7.526a	7.125bx	7.235bx	6.015c	5.825c			
	b	Shank	8.825b	8.125by	14.258a	14.925ax	15.25ax	**	***	***
		Loin	9.052b	8.925bx	14.954a	15.125ax	15.369ax			
		Shoulder	9.358b	9.423bx	14.136a	14.354ay	14.527ay			
TBARS		Shank	0.188cy	0.206cx	0.314by	0.32by	0.446a	***	***	***
		Loin	0.192dy	0.249cx	0.421bx	0.464ax	0.479a			
		Shoulder	0.212cx	0.185cy	0.338by	0.346by	0.443a			

[a,b,c,d] means with different letters within a row show the significant effects of processing in each cut; [x,y,z] means with different letters within the column show the significant effects of different cuts under the same processing conditions using Fisher's least significant difference ($p < 0.05$).

[e]ns, non-significant; *, p<0.05; **, p<0.01; ***, p<0.001.

The L*, a* and b* values in lamb meat were measured (Table 9) to investigate the effect of type of cuts and HPP treatments on meat colour. There were no significant differences in L*, a* and b* values observed between non-HPP treated control shank, loin and shoulder cuts. L*, a*and b* values were however significantly different with HPP treatment. The L* value of shank, loin and shoulder cuts were significantly increased when treated at 200 MPa, 300 MPa 400 MPa and 600 MPa compared to control samples of the corresponding cuts. Similarly Souza et al (2011) demonstrated that the L* values of three different pork muscles (*M*. Longissimus, *M*. Psoas major and *M*. riceps brachii) were significantly increased when HPP level increased from 0 MPa to 215MPa when held for 15 seconds. The increase in L* values ("whitening/ brightening") can be attributed to globin denaturation, heme release, ferrous ion oxidation and changes in water content (Cheftel & Culioli, 1997). In addition, the "whitening/brightening" effect of pressure could be attributed to denaturation of globin, release of haem, and oxidation of ferrous to ferric myoglobin at pressures more than 400 MPa (Campus, Flores, Martinez, & Toldrá, 2008). Meanwhile, the a* value was significantly decreased in shank and shoulder cuts after treatment

from 200 to 600 MPa. The a* value of loin cut was only significantly decreasd after treatment at 300 MPa. The b* value of shank, loin and shoulder cuts were significantly increased when treated at 300 MPa up to 600 MPa compared control samples of the corresponding cuts. McArdle, Marcos, Kerry, & Mullen (2010) investigated the colour changes of post rigor beef (*M. pectoralis profundus*) muscles pressurized for 20 min at 200, 300 and 400 MPa, at 20 °C and 40 °C. They concluded that beef (*M. pectoralis profundus*) muscles pressurized at 200 MPa had a lower impact on colour parameters than higher pressurisation levels (300 MPa and 400 MPa). Lamb *M. pectoralis profundus* samples treated at higher pressure levels (300 and 400 MPa) also had higher L* and b* values, and lower a* values than treated at a lower pressure level (200 MPa). The increase in *L** values may account for the "whitening" effect, which is attributed to the denaturation of the globin moiety of myoglobin (Trespalacios & Pla, 2007). Cheftel & Culioli (1995) concluded that meat discoloration through pressure processing may result from (1) a whitening effect in the range 200–350 MPa, due to globin denaturation and/or to heme displacement or release, and (2) oxidation of ferrous myoglobin to ferric metmyoglobin, at or above 400 MPa. Bak, Lindahl, Karlsson, & Orlien (2012) concluded that myosin was relatively sensitive to pressure at around 180 -300 MPa, and will denature to give translucent appearance in cooked meat. Ma & Ledward (2013) suggested that rare or medium rare steaks or pinkish lamb will not be an option in samples treated at pressures above 200 MPa. Therefore, meat discoloration could be a problem when marketing pressurized raw meat, as meat colour is one of the most vital criterion for consumers when purchasing meat.

4.2.2. Changes in lipid oxidation

The effect of HPP treatment on the level of lipid oxidation (TBARS value) in different lamb meat cuts was investigated and results are shown in Table 9. Two-way ANOVA results showed that the lipid oxidation of lamb samples was significantly ($p<0.05$) affected by both HPP treatment and type of cuts. The interaction between cuts and HPP treatment was significant as well. In

this study, there were significant differences in overall oxidation level with the three different types of cut. For control sample, the oxidation value of shoulder was higher ($P<0.05$) than loin and shank cuts. This is because that the content of C18:2n6, C18:3n6 and C22:2n6 in shoulder were significant higher than shank and loin (table 10). However, Kannan, Kouakou, & Gelaye (2001) concluded that there were no significant differences ($P>0.05$) in oxidation level in control shoulder and loin cuts.

There was no significant differences in lipid oxidation between control and samples treated at 200MPa. However, TBARS value significantly increased as pressure increased from 300 MPa. In this study, the higher levels of pressure (400 MPa and 600 MPa) also resulted in higher oxidation values in shank, loin and shoulder cuts of lamb. Several studies also reported that lipid oxidation increased as HPP pressure increased in turkey meat (Tuboly et al., 2003), chicken (Orlien et al., 2000), and pork mince (Cheah & Ledward, 1996). Similarly Cheah & Ledward (1996) investigated the effect of HPP (0-800 MPa for 20 min at 20 °C) on lipid oxidation of minced pork. Similar to our study, they found that the rate of lipid oxidation was slightly increased ($p>0.05$) from 0 to 200 MPa, but significantly increased for the samples treated at 300 MPa and above. HPP treatment at 215 MPa for 15 s, 33°C was found to inhibit the rate of lipid oxidation in pork loin (*M. longissimus dorsi*) compared to control (Souza et al., 2011). Similarly, lamb (*M. pectoralis profundis*) pressurized at 400 and 600 MPa at 60 °C resulted in the highest TBARS values compared to control samples (McArdle, Marcos, Mullen, & Kerry, 2013). Increased lipid oxidation after HPP, may be due to conformational changes of hemoproteins, which results in greater exposure of the catalytic heme group to unsaturated fatty acids (Bou et al., 2008). Lipid oxidation has been reported to occur with HPP treatment due to: 1) accessibility of iron from hemoproteins that increases with disruption of membrane; 2) iron released from hemoproteins facilitate lipid oxidation (Bajovic et al., 2012). These mechanisms may help explain the significant

increase in lipid oxidation observed in samples processed particularly at higher pressures.

4.2.3. Changes in fatty acid profiles

Fatty acid content influences the nutition, flavour, and texture of meat (Gerber, Scheeder, & Wenk, 2009). The fatty acid composition of shank, loin and shoulder meat cuts is summarised in Table 10. The dominant fatty acids in all samples included palmitic (C16:0), stearic (C18:0), oleic (C18:1n9c) and linoleic (18:2n6) acids. Lamb meat has been reported to contain more C16:0, C18:0 and C18:1n9 fatty acids (Kanatt, Chander, & Sharma, 2006; Vasta et al., 2013). Two-way ANOVA results in our study showed that the lipid oxidation of lamb samples was significantly ($p<0.05$) affected by HPP treatments and different cuts. The interaction of cut types and HPP treatments was significant as well.

In terms of cuts, the shoulder cut had significantly higher ($p<0.05$) amount of saturated fatty (SFA) (especially C16:0 and C18:0), monounsaturated fatty acids (MUFA) (C18:1n9c) and polyunsaturated fatty acids (PUFA) (C18:2n6c and C18:3n3) compared to loin cuts. Similarly, Badiani et al (2002) reported that SFA and PUFA were significantly higher in the shoulder (*M. infraspinatus*) than loin (*M. longissimus*) cuts of beef meat. The PUFA/SFA ratios for lamb is typically 0.1 but it can be higher in some muscles (Wood et al., 2004). The highest PUFA:SFA value was found in loin cut (0.355) compared to shank (0.221) and shoulder (0.199) in this study. It was also found that shoulder had the highest n6:n3 ratio than shank and loin cuts. The ratio of omega 3 to omega 6 PUFAs (n6:n3) ratio is important as a high ratio may promote incidences of cancers and coronary heart disease (Enser, Richardson, Wood, Gill, & Sheard, 2000).

The total SFA content was greater ($P < 0.05$) in control than in HPP treated shank and shoulder cuts. With respect to individual fatty acids, the significant changes in SFA were due mainly to the changes in C16:0 and C18:0 content. However, Huang et al (2015) reported that pork (M. *longissimus*)

treated with combinations of different pressure levels (200, 400, and 600 MPa) and temperatures (20 and 50 °C) for 20 min significantly decreased ($P < 0.05$) C18:0 content, and increased ($P < 0.05$) the C14:0 and C16:0 levels.

Total PUFA content significantly decreased in shank and shoulder cuts after HPP treatment at 200 MPa compared to control samples, and significantly decreased after HPP treatment at 300 MPa. With respect to individual fatty acids, the significant changes in PUFA were due mainly to changes in C18:1n9 and C18:2n6 content. The decrease in PUFA might be due to the increase in pressure that can increase oxidation level in lipids. PUFAs are not stable, and its oxidative stability is affected by the composition of fatty acids during processing, aging and retail display (Wood et al., 2008). HPP had a positive effect on PUFA/SFA ratios of shank and shoulder lamb cuts, PUFA/SFA ratio significantly increased in HPP treated samples at 300 MPa compared to control samples. However, the PUFA/SFA ratio range from 0.199 to 0.355, was not above recommended level 0.4. Banskalieva, Sahlu, & Goetsch (2000) similarly reported that the PUFA/SFA ratios for different muscles (M. *longissimus dorsi, M. biceps femoris, M. longissimus thoracis, M. gluteus medius*) in lamb meat ranged from 0.16 to 0.26.

Table 10 The fatty acid composition of different lamb cuts with and without HPP treatments at 200, 300, 400 and 600 MPa (mg/100 g dry meat)

Fatty acids	Cuts	Treatment					Significant of effect[a]		
		C	200	300	400	600	Cut	Treatment	Cut*Treatment
C16:1	Shank	0.687ax	0.477bx	0.445cy	0.418dy	0.422dx	***	***	***
	Loin	0.315z	0.282z	0.321y	0.314y	0.299y			
	Shoulder	0.77ax	0.787ax	0.576bx	0.53cx	0.473dx			
C17:1	Shank	0.387ax	0.333bx	0.275cx	0.267cx	0.272cx	***	***	***
	Loin	0.203ay	0.191aby	0.193aby	0.176by	0.177by			
	Shoulder	0.368ax	0.388ax	0.289bx	0.292bx	0.24cx			
C18:1n9	Shank	15.682ax	9.907by	9.373cy	9.028dy	9.154dx	***	***	***
	Loin	7.218ay	7.179az	6.149bz	6.157bz	6.143by			
	Shoulder	17.919ax	17.132bx	12.666cx	11.681dx	9.165ex			
C18:2n6	Shank	3.295ay	2.818by	2.773by	3.09ay	2.792by	***	***	***
	Loin	2.496az	2.283by	2.222bcy	2.219bcz	2.17cz			
	Shoulder	4.286ax	3.992bx	3.62cx	3.837cx	3.446ex			
C18:3n3	Shank	0.943ax	0.91ax	0.77by	0.729by	0.759by	***	***	***
	Loin	0.676z	0.677y	0.677z	0.632y	0.628y			
	Shoulder	1.064ax	0.933bx	1.099ax	0.966bx	0.826cx			
C18:3n6	Shank	0.234y	0.291x	0.359y	0.252x	0.247x	***	***	***
	Loin	0.18ay	0.184ay	0.184az	0.153by	0.151by			
	Shoulder	0.386ax	0.26bx	0.407ax	0.264bx	0.182cy			
C22:2n6	Shank	0.187ay	0.174abx	0.182a	0.177aby	0.122by	***	***	***
	Loin	0.188ay	0.167bx	0.17b	0.145cz	0.133dz			
	Shoulder	0.308ax	0.142cy	0.199b	0.219bx	0.177bcx			
C20:4n6	Shank	0.447ax	0.408bx	0.388bcy	0.383bcx	0.353c	***	***	***
	Loin	0.389ay	0.327by	0.343by	0.332by	0.335b			
	Shoulder	0.434ax	0.416ax	0.421ax	0.379bx	0.368b			
C20:5n3	Shank	0.341x	0.32	0.302	0.339x	0.314x	***	***	***
	Loin	0.368ax	0.319b	0.329b	0.33bx	0.326bx			
	Shoulder	0.315ay	0.299ab	0.304ab	0.28bcy	0.254cy			
C16:0	Shank	9.688ay	6.118by	5.607cy	5.721cy	5.273dx	***	***	***
	Loin	4.208z	4.035z	4.697y	4.15cy	4.624y			
	Shoulder	11.398ax	11.088ax	7.015bx	7.498bx	5.329cx			
C17:0	Shank	0.603ax	0.39by	0.369by	0.418bx	0.361bx	***	***	***
	Loin	0.285z	0.268z	0.317y	0.283y	0.297y			
	Shoulder	0.772ax	0.722bx	0.48cx	0.515cx	0.397dx			
C18:0	Shank	8.229ay	5.714bx	5.021cy	5.179cy	4.505dy	***	***	***
	Loin	4.295az	4.225ay	3.928bz	3.544cz	3.629cz			
	Shoulder	14.063ax	13.009bx	9.102cx	6.499dx	5.508ex			
C20:0	Shank	0.374ay	0.33by	0.283cy	0.27cdy	0.258dy	***	***	***
	Loin	0.244az	0.243az	0.238aby	0.231by	0.231by			
	Shoulder	0.422ax	0.434ax	0.359bx	0.338bx	0.288cx			
C21:0	Shank	5.076ay	4.427bx	3.321cy	3.366cy	2.609dy	***	***	***
	Loin	2.5abz	2.535ay	2.499aby	2.402bz	2.242cy			
	Shoulder	6.819ax	5.441bx	4.839cx	4.327dx	3.183ex			
C22:0	Shank	0.209y	0.202y	0.212y	0.204x	0.189	***	***	**
	Loin	0.183y	0.187y	0.207y	0.189y	0.185			
	Shoulder	0.247ax	0.222bx	0.224bx	0.209bx	0.193c			

Fatty acids	Cuts	Treatment					Significant of effect[e]		
		C	200	300	400	600	Cut	Treatment	Cut*Treatment
C23:0	Shank	0.167ax	0.13abx	0.105b	0.095b	0.099b	**	**	***
	Loin	0.136ay	0.105by	0.091c	0.095c	0.095c			
	Shoulder	0.109by	0.154ax	0.109b	0.1b	0.098b			
C24:0	Shank	0.358x	0.337x	0.314	0.347	0.298	***	***	***
	Loin	0.274y	0.276y	0.283	0.317	0.287			
	Shoulder	0.407ax	0.326bx	0.308b	0.329b	0.338b			
SFA	Shank	24.729ay	17.673by	15.258cy	15.625cy	13.617dy	***	***	***
	Loin	12.149az	11.90ay	12.285ay	11.236by	11.615bz			
	Shoulder	34.261ax	31.421bx	22.461cx	19.841cx	15.359dx			
MFA	Shank	16.766ay	10.727by	10.103bx	9.723bx	9.857bx	***	***	**
	Loin	7.745az	7.662az	6.673by	6.656by	6.628by			
	Shoulder	19.067ax	18.316ax	13.54bx	12.512bx	9.888cx			
PUFA	Shank	5.466ay	4.94by	4.793by	4.989by	4.606cy	***	1***	***
	Loin	4.316az	3.975az	3.944az	3.8305bz	3.762bz			
	Shoulder	6.811ax	6.061bx	6.068bx	5.964bx	5.272cx			
P:S	Shank	0.221cy	0.28cy	0.314b	0.319by	0.338a	***	***	***
	Loin	0.355x	0.334x	0.321	0.341x	0.324			
	Shoulder	0.199by	0.193bz	0.27a	0.301ay	0.343a			
n-3	Shank	1.291ay	1.236ax	1.078by	1.074by	1.08	***	***	***
	Loin	1.05y	1.002y	1.012y	0.969y	0.96			
	Shoulder	1.385ax	1.239bx	1.409ax	1.253bx	1.086b			
n-6	Shank	4.175ay	3.703by	3.715by	3.914ax	3.526bx	***	***	***
	Loin	3.265y	2.973z	2.932bz	2.862y	2.802y			
	Shoulder	5.426ax	4.822bx	4.659bx	4.711bx	4.186cx			
n-6/n-3	Shank	3.237by	2.995by	3.446ax	3.644ay	3.266by	***	***	***
	Loin	3.11y	2.969y	2.897y	2.955x	2.918y			
	Shoulder	3.919ax	3.894ax	3.308bx	3.761ax	3.855ax			
Total	Shank	46.96ay	33.339by	30.154cy	30.336cy	28.079cy	***	***	***
	Loin	24.21z	23.536z	22.901z	21.722z	22.005z			
	Shoulder	60.139ax	55.798bx	42.069cx	38.317cx	30.519dx			

[a,b,c,d] means with different letters within a row show the significant effects of processing in each cut; [x,y,z] means with different letters within the column show the significant effects of different cuts under the same processing conditions using Fisher's least significant difference ($p < 0.05$). SFA = C14:0+C16:0+C17:0+C18:0; C20:0; C21:0; C22:0; C24:0; MUFA = C16:1+ C18:1 cis-9; C20:1 cis-9; PUFA = C18:2n-6 +C18:3n-3; C20:2n-6;C20:3n-6;C20:5n-3; n−6 = C18:2n6+C20:2n6+C20:3n6; n−3 = C18:3n3+C20:5n3

[e]ns, non-significant; *, p<0.05; **, p<0.01; ***, p<0.001.

Multivariate analysis of fatty acids profiles

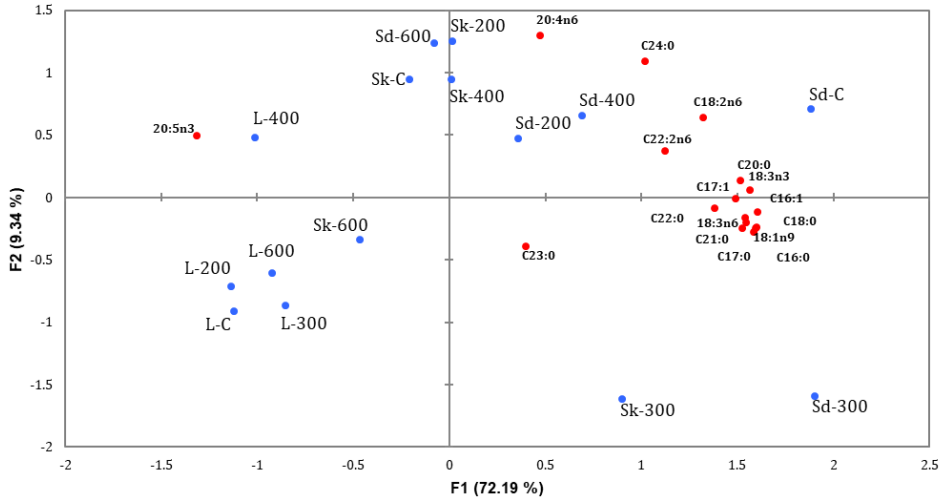

Figure 19 PCA bi-plots of F1 and F2 for the fatty acids composition of three lamb cuts treated with HPP at 200 MPa, 300 MPa, 400 MPa and 600MPa. C: control; 200-600: 200-600 MPa; Sd: Shoulder, Sk: Shank; L:loin

In order to illustrate differences between each treatment and each cut on the basis of individual fatty acids, PCA was carried out to assess the variation in fatty acids from three lamb cuts treated with HPP at 200 MPa, 300 MPa, 400 MPa and 600MPa. The PCA shown in Fig. 19 described 72.19% and 9.34% of the total variation in factor 1 (F1) and factor 2 (F2), respectively. Only control shoulder cut sample (Sd-C) had high positive scores that corresponded to high loadings of fatty acids, while control shank and loin cuts had low negative values along F1. PUFA (such as C18:2n6 and C22:2n6) were significantly higher ($p<0.05$) in control shoulder cut sample compared to control shank and loin cuts (Table 10). This result may be correlated to the higher TBARS value in control shoulder cut sample compared to shank and loin cuts as shown in Table 9.

Shoulder cut samples treated with HPP at 200, 300 and 400 MPa had high positive scores that corresponded to high loadings of fatty acids, while HPP treated at 600MPa shoulder cut sample had low negative scores along F1. C18:3n3, C18:3n6, C22:2n6 and C20:5n3 content were significantly higher ($p<0.05$) in shoulder cut samples treated with HPP at 200, 300 and 400 MP compared to 600MPa (Table 10). Control and all HPP treated loin cut samples corresponded to negative scores along F1. This finding is supported

by results in Table 10 that showed no significant changes in C16:0, C17:0, C24:0, C16:1 and C18:3n3 fatty acids in loin cuts before and after HPP treatment.

4.2.4. Changes in free amino acid profiles

Free amino acids may influence brothy and meaty flavours, and are known precursors of meat flavour (Suzuki et al., 1994). The effect of HPP treatments at different pressure levels with different cuts of lamb meat on free amino acids content was summarized in Table 11. Significantly higher ($p<0.05$) total free amino acids content was found in loin compared to shoulder and shank cuts. Aristoy & Toldrá(1998) reported that total free amino acids content in *M. longissimus dorsi* (loin) was significantly higher ($p<0.05$) than in *M. semimebranosus* (topside) for pig meat. Howerver, total free amino acids content in *M. longissimus dorsi* was significantly lower ($p<0.05$) than in *M. semitendinosus, M. biceps femoris* and *M. semimembranosus* for beef meat (Franco et al., 2010).

Table 11 The free amino acid composition of different lamb cuts with and without HPP treatments at 200, 300, 400 and 600 MPa (mg/100 g dry meat)

Free amino acids		Cuts	Treatment					Significant of effect[e]		
			C	200	300	400	600	Cut	Treatment	Cut*Treatment
Essential amino acids	His	Shank	0.15	0.143	0.143	0.124y	0.136y	ns	ns	**
		Loin	0.114b	0.12b	0.123b	0.168ax	0.161ax			
		Shoulder	0.144	0.147	0.143	0.126y	0.153y			
	Ile	Shank	0.277ax	0.199bx	0.114cy	0.117cy	0.148bcy	**	**	***
		Loin	0.168by	0.174bx	0.187abx	0.208abx	0.254ax			
		Shoulder	0.127by	0.125by	0.124by	0.2ax	0.196ay			
	Leu	Shank	0.186ax	0.187ax	0.163aby	0.134by	0.157aby	***	**	***
		Loin	0.149cy	0.168bcx	0.184bcx	0.197bx	0.245ax			
		Shoulder	0.137cz	0.153bcy	0.145bcz	0.17ax	0.155aby			
	Lys	Shank	0.124ax	0.108aby	0.094bc	0.084cy	0.103abcy	**	*	***
		Loin	0.107bx	0.109by	0.093b	0.15ax	0.143ax			
		Shoulder	0.083cy	0.128ax	0.091bc	0.094bcy	0.112aby			
	Met	Shank	0.065bx	0.059b	0.054bc	0.037cy	0.143ax	**	***	***
		Loin	0.044by	0.047b	0.049b	0.079ax	0.074ay			
		Shoulder	0.048aby	0.045b	0.061ab	0.065ax	0.064aby			
	Phe	Shank	0.171c	0.216abx	0.18bc	0.124dy	0.237ax	*	**	
		Loin	0.17b	0.159by	0.174ab	0.18abx	0.215ax			
		Shoulder	0.157ab	0.171aby	0.169ab	0.142bxy	0.183axy			
	Thr	Shank	0.145cdy	0.252ax	0.228abx	0.133dy	0.186bcy	**	**	***
		Loin	0.138by	0.257ax	0.231ax	0.247ax	0.277ax			
		Shoulder	0.204abcy	0.162cy	0.169bcy	0.211abx	0.234ax			
	Val	Shank	0.231abx	0.268ax	0.248abx	0.175by	0.26ay	*	*	***
		Loin	0.18cy	0.218bcy	0.272abx	0.285abx	0.329ax			
		Shoulder	0.18cdy	0.204bcy	0.163dy	0.225bx	0.308ax			

Free amino acids		Cuts	Treatment					Significant of effect[c]		
			C	200	300	400	600	Cut	Treatment	Cut*Treatment
Non-essential amino acids	Asp	Shank	0.824dy	1.382b	1.113cy	1.061cdy	2.107ax	**	**	***
		Loin	1.077by	1.294ab	1.523ax	1.543ax	1.669ax			
		Shoulder	1.531ax	1.262ab	0.99by	0.978by	0.999by			
	Glu	Shank	0.808bx	1.192ax	0.61cy	0.554cy	0.854by	ns	***	***
		Loin	0.19cy	0.735by	1.134ax	1.017ax	1.211ax			
		Shoulder	0.675cx	0.753bcy	0.818abx	0.921ax	0.829aby			
	Trp	Shank	0.082ax	0.064ab	0.065ab	0.058by	0.075aby	**	**	**
		Loin	0.054dy	0.06cd	0.073bc	0.075bx	0.098ax			
		Shoulder	0.06y	0.06	0.065	0.054y	0.058y			
	Tyr	Shank	0.203ax	0.132bc	0.162bx	0.093dx	0.107cdx	***	***	***
		Loin	0.117by	0.157b	0.138by	0.109bx	0.265ax			
		Shoulder	0.109by	0.107b	0.173ax	0.077cy	0.095by			
	Ala	Shank	0.752bx	1.046ax	0.846ab	0.64b	0.704by	***	**	**
		Loin	0.543cy	0.579bcy	0.732ab	0.751ab	0.784ay			
		Shoulder	0.84bx	0.976bx	0.844b	0.801b	1.314ax			
	Gly	Shank	0.734bx	0.813abx	0.75abx	0.562cx	0.899ax	***	**	*
		Loin	0.531by	0.613aby	0.61aby	0.588abx	0.703ax			
		Shoulder	0.504ay	0.564ay	0.505az	0.332by	0.497ay			
	Pro	Shank	0.099abx	0.123ax	0.126ax	0.06by	0.108a	**	ns	*
		Loin	0.064by	0.053by	0.068by	0.095ax	0.098a			
		Shoulder	0.071y	0.085y	0.075y	0.099x	0.102			
	Ser	Shank	0.141by	0.321ax	0.322ax	0.143by	0.304a	ns	**	**
		Loin	0.218x	0.196y	0.256y	0.264x	0.243			
		Shoulder	0.186xy	0.242xy	0.221y	0.245x	0.241			
Total		Shank	4.993bx	6.503ax	5.218by	4.1cy	6.529ax	*	**	***
		Loin	3.864cy	4.939bcy	5.847bx	5.956bx	6.769ax			
		Shoulder	5.056abx	5.185aby	4.758bz	4.739by	5.538ay			

[a,b] means with different letters in row show a significant effect of processing in each cut; [x,y,] means with different letters in column show a significant effect of a cut in each processing using Fisher's least significant difference ($p < 0.05$).ASP: aspartic acid. GlLU: glutamic acid. GLY: glycine. HIS: histidine. ILE: isoleucine. LEU: leucine. LYS: lysine. MET: methionine. PHE: phenylalanine. PRO: proline. SER: serine. THR: threonine. TRP: tryptophan. TYR: tyrosine. VAL: valine.

[c]ns, non-significant; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.

In terms of HPP treatment in this study, high-pressure treatment of shoulder cut had no adverse effect on total free amino acid composition compared to the corresponding control sample. Similarly, Suzuki et al (1994) reported that pressure treatments between 200 to 400 MPa at ambient temperature did not influence the amino acids composition of beef shoulder muscles. With respect to individual free amino acids, there were no significant changes in Trp, His, Pro, and Ser content in shoulder cut samples.

The concentration of total free amino acids were significantly higher in the shank cut when treated at both 200 MPa and 600 MPa compared to the corresponding control sample. This was mainly due to the increases in Asp, Glu, Phe, Ala, Thr and Ser content. Ohmori, Taji, Shigehisa, Hayashi, & Rikimaru (1991) reported that a higher level of free amino acids could be due to the extent the overall autolytic activity of raw beef meat when HPP was applied at between 100 and 300 MPa (10 min at 25 °C), especially at 100 MPa.

The total free amino acids of HPP treated smples were higher than control. In fact, it was the highest with HPP treatment at 600 MPa compared to other HPP treated samples. His, Leu, Lys, Met, and Pro content significantly increased when HPP treated at 400 MPa, while Ile,Phe, Tyr, and Gly content significantly increased when HPP treated at 600 MPa. Suzuki et al (1994) reported that Ser, Glu, Gly and Ala content gradually increased with increasing pressure applied to lean beef meat up to 200 MPa. Proteolysis leads to increased amino acid concentration, while amino acid metabolism decreases the concentration of certain amino acids (Ueno et al., 2009).

Multivariate study of free amino acids profile

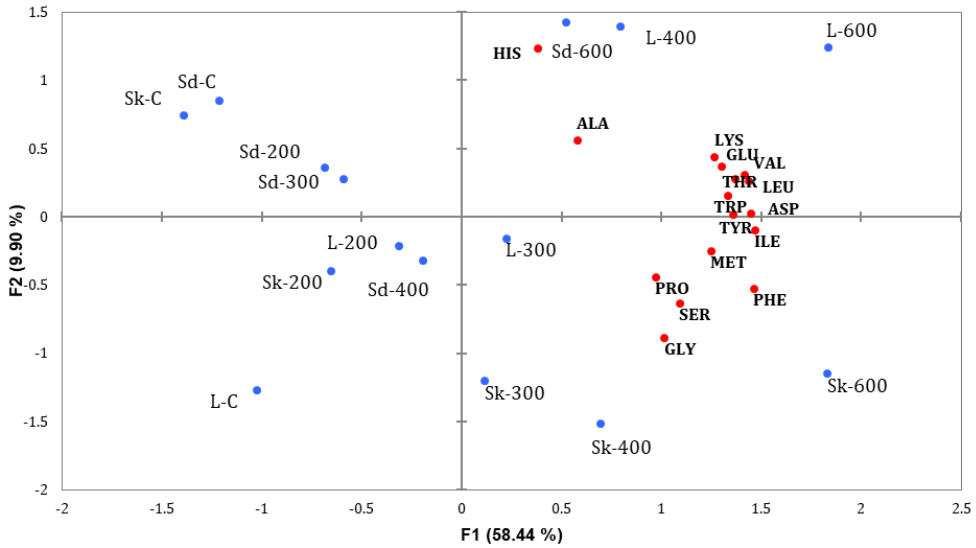

Figure 20 PCA bi-plots of F1 and F2 for the fatty acids of three lamb cuts treated with HPP at 200 MPa, 300 MPa, 400 MPa and 600MPa. C: control; 200-600: 200-600 MPa; Sd: Shoulder, Sk: Shank; L:loin

In order to illustrate differences between each treatment and each cut on the basis of individual free amino acids compounds, PCA was carried out to assess the variation in free amino acids content of the three lamb cuts treated with HPP at 200 MPa, 300 MPa, 400 MPa and 600MPa. The PCA shown in Fig. 20 described 58.44% and 9.90% of the total variation in factor 1 (F1) and factor 2 (F2), respectively.

Loin and shank cut samples treated with HPP at 300, 400 and 600 MPa had high positive scores that corresponded to high loadings of free amino acids. Val and Ala were significantly higher ($p<0.05$) in HPP treated at 600MPa shoulder cut sample compared to other shoulder cut samples (Table 11). This is supported by results shown in Table 11 that showed Lys, Ile, Leu and Glu to be significantly higher in loin cut samples treated above 300 MPa samples than control and HPP treated samples at 200MPa. HPP treated shank cut sample at 600MPa had positive scores that also corresponded to high loadings of fatty acids. Phe was significantly higher ($p<0.05$) in HPP treated shank cut sample at 600MPa compared to control and HPP treated shank cut samples at 200MPa (Table 11).

Control samples for all three cuts, shoulder cuts treated with HPP at 200, 300 and 400MPa, as well as HPP treated loin and shank cuts at 200MPa had negative scores along F1. Met and Asp were significantly lower ($p<0.05$) in control and HPP treated shank cut samples at 200MPa compared to HPP treated shank cut samples at 600MPa (Table 11). His, Lys,Met,Leu,Trp Tyr and Pro were significant lower ($p<0.05$) in control and HPP treated loin cut samples at 200MPa compared to HPP treated loin cut sample at 400, and 600 MPa (Table 11).

4.2.5. Panel dominance curves

TDS curves distinguished the effect of HPP pressure and different cuts in terms of dominant sensory attributes of the samples. Fig. 21 showed that all samples were dominant in terms of meaty, browned, juicy and livery attributes during the mastication period, and then oxidized thereafter. Meaty was the first dominant sensation in all samples with the dominance rates starting at over 50% dominance rate and then decreasing to below chance level in less than 10 s. Dominance rate of the browned attribute increased from almost the start of mastication and reached a maximum in the first 3-5 s, then rapidly decreased to below chance level after 10 s of the mastication period. Starting from 11 s, oxidized became the dominant attribute above significance level until the end of mastication (except Sk-C (1), Sk-200 (2), L-600 (9), and Sd-300 (13)). The attributes of livery and juicy were occasionally above the significant level, and only lasted a few seconds (except Sk-600, L-600 and Sd-600).

In the shank cuts (1-5), meaty started at around 60% dominance rate (except for Sk-600 (5)), and then decreased to below chance level at 7 s. Meaty also became significant after 11 s in Sk-C (1) and fluctuated around the significant level until the end of mastication. Sk-C (1), Sk-300 (3) and Sk-600 (5) samples were dominant in browned attribute compared to Sk-200 (2) and Sk-400 (4). Juicy was only dominant in Sk-400 (4) sample from 5 to 7 s. Livery was dominant in Sk-200 (2) from 30 to 36 s, while in Sk-600 (5) fluctuated around significant level from 23 to 40 s. In Sk-C (1) oxidized was dominant from 45

to 55 s and 60 to 70 s period, while oxidized was dominant in Sk-200 (2) from 20 s onwards and achieved 50% dominance rate between 50 and 80 s. Oxidized in Sk-300 (3), Sk-400 (4) and Sk-600 (5) was dominant starting at 10 s and fluctuated around the significant level until the end of mastication.

In the loin cut (6-10), meaty started at around 60% dominance rate (except for L-300 (8)), and then decreased to below chance level at 3 s. With L-C (6) and L-300 (8) samples, meaty attribute was dominant from 40 to 80 s and 50 to 75 s, respectively. Browned was dominant from 2 to 8 s in all samples except for L-400 (9). Juicy was only dominant in L-200 (7) from 5 to 8 s. Livery was dominant in L-300 (8) and L-600 (10) samples between 20 to 30 s. L-C (6) and L-400 (9) were dominant in oxidized attribute after 10 s and fluctuated around the significant level until the end of mastication. Oxidized became dominant in L-200 (7) from 10 to 80 s with 50% dominance rate between 30 and 50 s. Oxidized was only dominant in L-300 (8) and L-600 (10) samples from 5 to 15 s and 25 to 40 s at around 40% and 45% dominance rate, respectively.

In shoulder cuts (11-15), meaty started at above 60% dominance rate (except for Sd-C (11)), and then decreased to below significance level at about 4 s, except for Sd-400 (14) sample that decreased to 32.6 % dominance rate at 8 s. Browned was dominant in all shoulder samples during the first 10 s of mastication, except in Sd-300 (13). Juicy and livery were dominant in Sd-600 (15) between 10-18 s and 28-40 s, respectively. Oxidized was dominant in Sd-C (11) sample that increased from 32.6 % to 48% dominance rate between 10 to 13 s and dropped back 32.6 % dominance rate at 18 s. Sd-200 (12) sample was dominant in oxidized attribute between 8 and 40 s, while oxidized in Sd-300 (13) became dominant from 30 s until the end of mastication. Sd-400 (14) had shorter duration of oxidized than Sd-300 (13). In addition, Sd-600 (15) sample was dominant in oxidized attribute with about 52% dominance rate between 45 to 80 s.

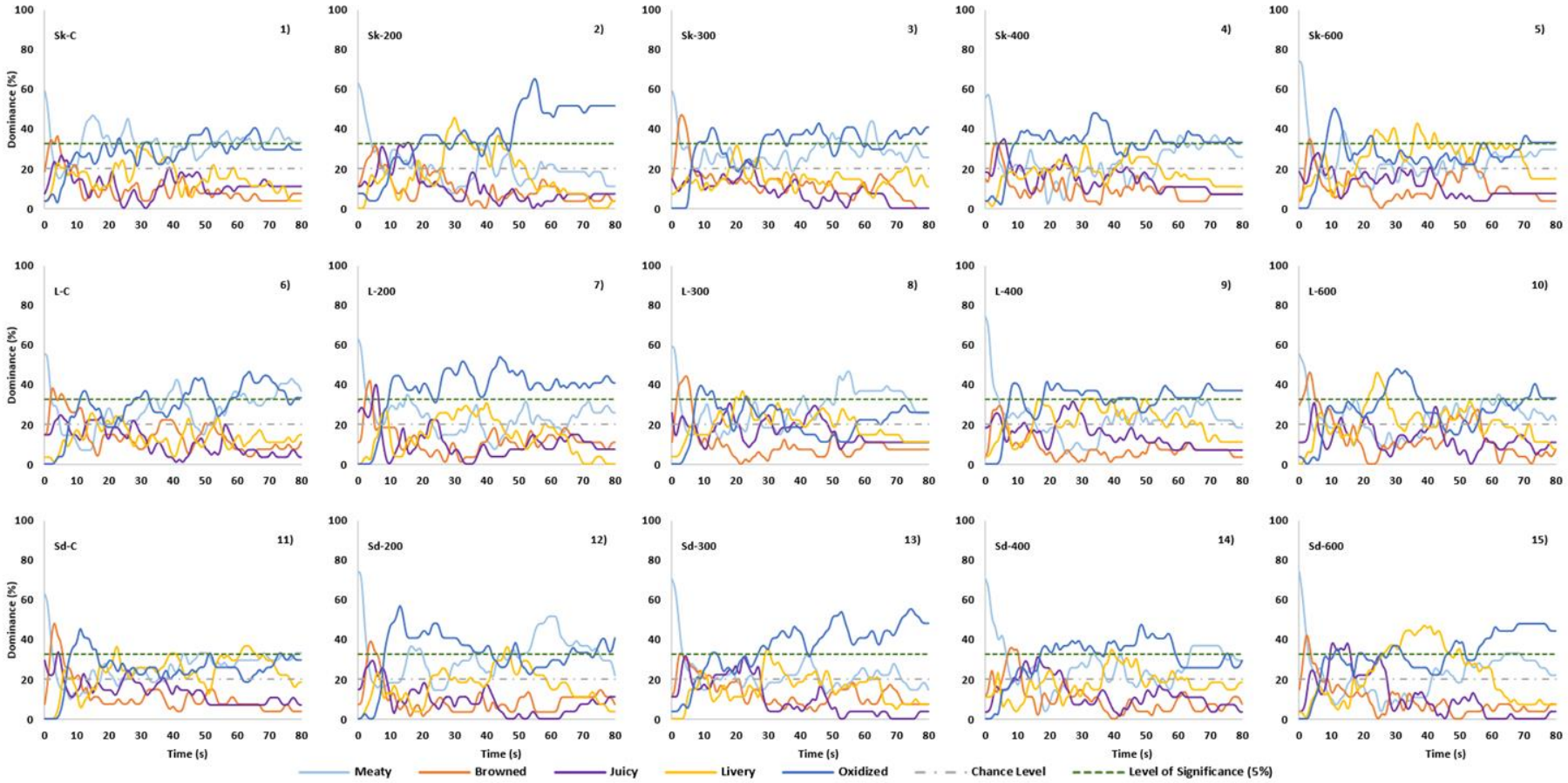

Figure 21 TDS curves for sensory attributes of different lamb cuts with and without pulsed HPP treatments at 200, 300, 400 and 600 MPa. Sk: shank; L: loin; Sd: shoulder.

Canonical variate analysis

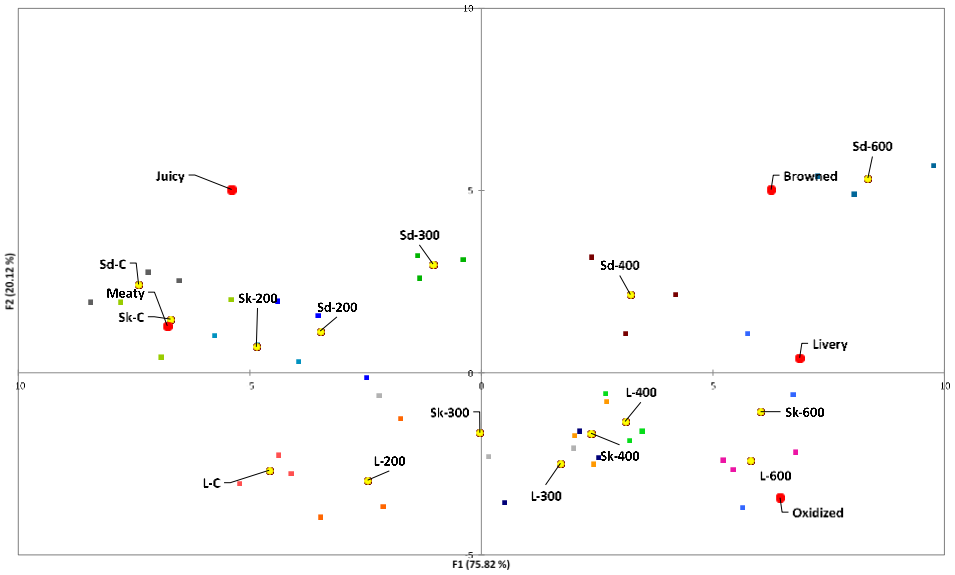

Figure 22 CVA Biplot of dominance durations of sensations of lamb cut with and without HPP treatments at 200, 300, 400 and 600 MPa.Hotelling-Lawley trace MANOVA test showed significant product differences ($F = 15.655$; $p < 0.05$) based on sensory attributes. Sk: shank; L: loin; Sd: shoulder.

All samples were discriminated by CVA with a high variance for sensory data at 95.45%. Hotelling Lawley MANOVA ($F = 15.414$; $p<0.01$) showed significant differences between the samples in terms of the temporal flavor attributes measured by TDS (Figure 22). F1 explained 75.82% of the variance, separating the meat samples in terms of HPP treatments with different pressure levels. Negative scores along F1 corresponded to control samples of all cuts and almost all samples treated with HPP at 200 and 300 MPa (except L-300) samples. It can be seen that control and samples treated at mild pressure levels (200 MPa) were correlated with meaty and juicy, especially in shank and shoulder cuts. The application of 300 MPa pressure also significantly increased juiciness of pork frankfurters (Crehan, Troy, & Buckley, 2000). Positive loadings corresponded to samples treated with HPP at 400 and 600 MPa. Samples treated at the highest-pressure levels (600 MPa) were correlated with browned (Sd-600), livery (SK-600) and oxidized (L-600) attributes. Rivas-Cañedo, Juez-Ojeda, Nuñez, & Fernández-García (2011) reported that high concentration of pyrazines that can contribute to browned flavor were found in sliced cooked pork shoulder treated at 400 MPa for 10 min at 12 °C compared to control sample. Oxidized attribute may be due to lipid oxidation. In this study, the higher levels of pressure (400

MPa and 600 MPa) resulted in higher oxidation values in shank, loin and shoulder cuts of lamb (Table 9). In addition, shank cut treated at 600 MPa was correlated with livery. Livery flavor is a complex trait that cannot be related to any single characteristic (Yancey et al., 2006). Livery flavor in this study may be attributed to the high free amino acids produced when content when treated at 600 MPa (Table 11). Methionine is an important precursor of sulphur volatile compounds meat that may interact with carbonyl compounds to produce the livery flavor attribute in pork (Mussinan & Walradt, 1974), beef (Werkhoff et al., 1996) and lamb (Lorenz et al., 1983) liver. Furthermore, livery flavor can be related to heme iron and/or myoglobin levels (Calkins & Cuppett, 2006; Yancey et al., 2006). Muscles often exhibiting liver-like flavor, such as the psoas major (loin) and gluteus medius (round) generally have higher levels of heme iron and/or myoglobin. Calkins and Cuppett (2006) reported that livery flavor increases as iron content increases.

4.2.6. Conclusion

HPP significantly affected physicochemical properties (colour, lipid oxidation, fatty acids and free amino acids) and sensory characteristics of the three different lamb cuts. Lamb meat discoloration occurred when HPP was applied at pressure levels of more than 400MPa. Lipid oxidation similarly increased significantly with pressure after 200 or 300 MPa depending on type of meat cuts compared to the corresponding control cuts. SFA and PUFA content decreased in shank and shoulder cuts with increase in pressure levels after 200 or 300 MPa. Free amino acids content increased in shank and loin cuts with pressure increase after 200 MPa, and in shoulder cut after 400 MPa. HPP processing affected the temporal flavour profiles meat samples. At higher pressure levels of 400 and 600 MPa, meat samples were associated with browned, livery and oxidized flavour. These results imply that when carrying out HPP, it is important to consider the pressure levels applied and the type of meat cuts used to achieve a product with desirable physical, chemical and sensory characteristics.

4.3. The impact of pulsed electric field (PEF) on physicochemical properties of chilled and frozen-thawed lamb meat with seven different cuts

The New Zealand red meat sector has been a principal driver of New Zealand's economy and identity. The demand for high-quality, convenient meat products has propelled the meat industry

to find a way to further utilize the whole carcass and maximize the yield of saleable product due to the high cost of meat production (Desmond & Troy, 2001). Therefore, extending low-value cuts is an important way to enhance their market value. Consumers demand lamb meat to be lean and palatable, with good nutritional attributes. These three key drivers influence the purchase and "willingness to pay" decisions of consumers (Pethick, Banks, Hales, & Ross, 2006). New Zealand lamb is currently exported as a frozen product. With improved hygienic processing, packaging and chilling technologies, New Zealand meat processors have been able to supply chilled unfrozen lamb cuts to overseas markets (Y. H. B. Kim et al., 2011). Fresh chilled meat however has always been considered a higher quality product (ie. tenderness and drip loss) that fetch higher prices than frozen meat.

Recent studies have found that aging meat prior to freezing meat can increase tenderness and minimize drip loss in beef (Kim et al., 2011), lamb (Choe, Stuart, & Kim, 2016) and venison (Wiklund, Farouk, Stuart, & Dobbie, 2009). However, meat quality changes in frozen/thawed meat (Li & Sun, 2002). Leygonie, Britz, & Hoffman (2012) reported that the formation of ice crystals during freezing not only causes physical and structural damages to muscle tissues, but also lead to various changes in lipid oxidation, fatty, acids and volatile composition. However, only Faridnia et al (2015) investigated the effects of freezing as a. pre-treatment prior to PEF treatment on the physicochemical characteristics of *semitendinosus* beef muscle. They found that frozen-thawing initiated primary lipid oxidation in the meat. This can lead to radical secondary lipid oxidation upon thawing, leading to adverse changes in colour, flavour and nutritional value (Leygonie et al., 2012).

Pulsed electric field (PEF) technology is a non-thermal processing method with low energy requirements that minimizes quality deterioration of food. This technology has been widely used in industrial pasteurization of liquid foods such as beer, fruit juice and milk (Bermúdez-Aguirre, Fernández, Esquivel, Dunne, & Barbosa-Cánovas, 2011; Milani, Alkhafaji, & Silva, 2015; Timmermans et al., 2014). Recently, more studies have been conducted on muscle foods. It has been reported that the use of PEF in muscle foods (especially in beef) can enhance cell permeability due to electroporation and consequently enhance proteolysis that contributes to tenderisation (Bekhit, van de Ven, Suwandy, Fahri, & Hopkins, 2014; Suwandy, Carne, van deVen,

Bekhit, & Hopkins, 2015; Jaeger, Balasa, & Knorr, 2008; Toepfl, Heinz, & Knorr, 2007). Proteolysis can influence the quality characteristics of meat during processing (such as aging and dry-curing), and is an important source of flavour compounds (free amino acids and small peptides). During processing, meat proteins undergo intensive proteolysis to produce relatively high amounts of free amino acids (Toldrá and Flores, 1998). Free amino acids (FAA) are important precursors of flavor compounds of meats that can influence palatability (Baryłko-Pikielna & Kostyra, 2007; Chiang et al., 2007). FAA are highly correlated with the development of flavour in dry-cured meat products. Sweet taste is associated with tryptophan, phenylalanine, histidine, tyrosine, leucine, glycine and alanine; bitter taste with valine; and meaty flavor with glutamic acid (Janes et al., 2012). Certain FAA (e.g., glutamate, glycine, and β-alanine) provide "meaty flavor" to improve appetite and gastrointestinal function (San Gabriel and Uneyama, 2013). During cooking, FAA can react with sugars and possibly lipid oxidation products to produce heterocyclic compounds that contribute to the flavor profiles of cooked foods (Mottram, 1998). In addition, changes in the content of FAA can be used for measuring proteolytic activity and this has been carried out on the process of ripening dry-cured ham (Pérez-Palacios et al., 2010). Therefore, it is important to understand the influence of PEF processing on free amino acids profile of meat.

Foods do not only undergo a series of physical and chemical reactions during mastication and salivation, but also results in flavor and textural changes. The way food is broken down in the mouth affects both texture perception and consumer preference (Albert, Salvador, Schlich, & Fiszman, 2012). Conventional static sensory assessment of food carried out at a single point evaluation by panelist therefore does not provide an accurate description of changes in sensory attribute during mastication. As flavor is a dynamic phenomenon, application of temporal sensory evaluation methods like Temporal Dominance of Sensations (TDS) have become increasingly important to understand the changes in sensory perception over the time of consumption. With TDS, panelists are trained and several several attributes can be evaluated simultaneously throughout consumption (Di Monaco, Su, Masi, & Cavella, 2014). This method has been employed to study the perception of foods like fish sticks (Albert et al., 2012), low-sodium Mozzarella cheese (Rodrigues, Gonçalves, Pereira, Carneiro, & Pinheiro, 2014), bread

(Panouillé, Saint-Eve, Déléris, Le Bleis, & Souchon, 2014), wines (Meillon et al., 2010), and sausage (Devezeaux de Lavergne, Derks, Ketel, deWijk, & Stieger, 2015).

Studies have demonstrated that texture and the extent of lipid oxidation in meat are influenced by PEF processing. However there has been no detailed investigation to understand changes in fatty acids, amino acids and sensory properties of lamb meat of different cuts processed using PEF at varying pressure levels. This study therefore sets out to assess the effects of: PEF processing of seven different lamb meat cuts (knuckle, loin, rump, rib, shank, shoulder and topside), and effects of chilled storage (0 and 7 days) of meat on 1) physicochemical characteristics (colour, cooking loss, fatty acids and free amino acids) of chilled and frozen-thawed lamb meat; 2) temporal flavour changes of cooked lamb meat using TDS.

4.3.1. Effect of PEF treatment on temperature, conductivity and pH

The actual electric field strength ranged from 1.0 to 1.3 kV cm^{-1} for chilled meat, and 1.0-1.8 kV cm^{-1} for frozen-thawed meat. Generally, electroporation occurs when the electric field strength exceeds 0.5 kV cm^{-1} electric field strength in animal cells, leading to a transient increase of membrane permeability (Alahakoon et al., 2016). Table 12 summarizes the PEF parameters, and changes in temperature, conductivity and pH of PEF treated lamb meat cuts in this study. Overall, there is a difference in conductivity, temperature and pH values between the seven lamb cuts. For example, the changes in conductivity was 4.09 (S/m) for chilled shoulder lamb cut and 1.43(S/m) for chilled topside. Brackebusch, McKeith, Carr, & McLaren (1991), Cho et al (2005), and Bekhit, Suwandy, Carne, van de Ven, & Hopkins (2016) reported that the difference in conductivity, temperature and pH between each muscle may be due to differences in their fatty acid composition, chemical composition and potential differences in minerals and vitamins contents.

Table 12 Pulsed electric field processing parameters and changes in temperature, conductivity and pH during treatment of chilled and frozen-thawed lamb meat cuts

Pre-treatment	Cuts	Changes in Temperature (°C)	Changes in Conductivity (S/m)	Changes in pH	Pulse voltage (kV)	Pulse current (A)	Pulse power (kW)	Pulse energy (J)	Pulse resistance (ohm)	Energy density (kJ/kg)
Chilled	Shoulder (Sd)	10.46±2.1	4.09±0.5	-0.11±0.01	4.34±0.11	87.52±1.54	378.29±3.38	6.43±0.07	49.36±2.31	95.58±4.11
	Rib (Rib)	17.1±3.1	2.68±0.8	0.66±0.02	4.58±0.13	84.46±1.71	385.2±3.11	6.56±0.05	54±2.35	109.14±2.88
	Loin (L)	10.32±1.5	3.25±0.7	0.03±0.01	4.03±0.18	91.99±2.38	371.25±6.09	6.31±0.1	43.92±2.97	92.59±9.26
	Knuckle (K)	12.85±3.2	1.51±0.2	0.26±0.02	4.4±0.2	86.38±2.73	381.38±5.21	6.48±0.1	51.38±3.85	98.38±6.22
	Rump (R)	11.89±2.8	1.48±0.3	0.09±0.03	4.31±0.19	87.82±2.76	377.58±5.47	6.43±0.1	49.25±4.05	103.11±10.26
	Shank (Sk)	11.37±1.7	1.87±0.5	0.18±0.01	4.59±0.24	84.31±3.47	385.88±6.33	6.56±0.11	54.75±5.37	106.09±11.92
	Topside (T)	13±1.4	1.43±0.4	0.21±0.05	4.33±0.26	87.94±3.52	376.75±6.94	6.4±0.12	49.08±5.11	96.75±9.14
Frozen-thawed	Shoulder (Sd)	7.57±1.3	4.1±0.3	-0.13±0.04	4.56±0.23	85.63±3.25	383.14±6.34	6.51±0.12	52.43±4.83	104.55±6.28
	Rib (Rib)	12.03±2.5	3.9±0.4	0.23±0.01	4.92±0.58	78.86±7.57	388.56±6.17	6.61±0.12	64.39±14.17	109.1±10.5
	Loin (L)	7.84±0.8	2.62±0.8	-0.04±0.01	3.81±0.13	94.97±1.83	362.71±6.13	6.16±0.11	40.29±2.09	87.74±11.89
	Knuckle (K)	11.15±4.3	2.81±0.8	-0.06±0.01	4.09±0.21	91.16±2.89	371.33±7.96	6.29±0.13	44.67±3.7	94.71±11.29
	Rump (R)	11.24±3.2	3.5±0.9	-0.05±0.02	4.08±0.19	91.78±2.68	374.5±7.45	6.37±0.14	44.5±3.51	102.33±7.65
	Shank (Sk)	12.41±2.4	4.74±0.2	0.18±0.05	4.36±0.27	87.63±3.49	381.22±6.04	6.49±0.11	50±5.02	106.5±16.06
	Topside (T)	10.25±1.8	2.91±0.4	-0.02±0.01	4.06±0.21	92.2±3.18	867.33±8.57	6.25±0.14	43±3.9	91.23±6.96

Mean ± standard deviation

The temperature of all PEF treated samples increased immediately after treatment from 10.32 to 17.1 °C for chilled meat and 7.57 to 12.41 °C for frozen-thawed meat. Lindgren, Aronsson, Galt, & Ohlsson (2002) reported that the temperature increase was due to the transformation of energy input developed in the temperature chamber during PEF treatment that lead to mild ohmic heating. The application of PEF treatment (electric field strength: 1.1–2.8 kV cm^{-1}; energy density: 12.7–226 kJ/kg, frequency: 5–200 Hz and pulse number: 152–300) on beef *semitendinosus* muscle increased the meat temperature from 5 to 30 °C (O'Dowd et al., 2013). Bekhit, van de Ven, Suwandy, Fahri, & Hopkins (2014) also reported a change in the temperature of PEF (electric field strength: 0.27–0.56 kV cm^{-1}; energy density: 3.1–73.2 kJ/kg, frequency: 0–90 Hz and pulse number: 0–2724) treated beef *semimembranosus* and *longissimus lumborum* that increased from 0.4 to 8.0 °C. However, Alahakoon et al (2016) stated that the higher temperature change due to PEF may decrease the activity of the enzymes involved in proteolysis. Suwandy, Carne, van de Ven, Bekhit, & Hopkins (2015) reported that the highest PEF intensity (10 kV and 90) increased the temperature to an average of 28.9 °C that can result in the development of heat toughening in beef *M*. longissimus lumborum (LL) and *M*. semimembranosus (SM) muscles samples (Suwandy et al. 2015). Bekhit et al (2016) also reported that protein denaturation and reduced proteolysis may occur with repeated PEF treatments on beef *M*. *longissimus lumborum* muscle (changes in average temperature 6.5–13.4 °C) and *M. semimembranosus* (1.8–6.7 °C).

The conductivity of all lamb meat samples immediately increased after PEF treatment. The change in conductivity ranged from 2.62-4.74 S/m. Faridnia et al (2015) stated that PEF (electric field strength:1.4 kV cm^{-1}, pulse width: 20 μs, frequency: 50 Hz) enhanced transport of ions that contributed towards modification of the intracellular environment of beef *M.semitendinosus* muscles. In this study, the conductivity of frozen-thawed meat cuts (except shoulder and loin cuts) were higher than chilled cuts. This

may be due to the influence of the meat water fraction as a result of the frozen-thaw process that results in the damage of cell membrane, which increased the conductivity of meat (Faridnia et al., 2015). Lawrie & Ledward (2006) further explained that concentrated residues (proteins, carbohydrates, lipids etc) increased when the water is frozen, thereby disrupting the homeostasis of the complex meat system. Benjakul & Bauer (2001) further stated that when muscle tissue are frozen and thawed, damage in cell membranes may occur due to ice crystals.

In this study, pH value was not significantly changed before and after PEF treatments, which may be due to the low frequency PEF treatment (1-50 Hz) used in this study. Similarly Bekhit et al (2016) reported no apparent trend observed in pH changes in beef *M. longissimus lumborum* and *M. semimembranosus* muscles after PEF treatment at 10 kV cm^{-1}, 90 Hz, 20 µs. Table 12 shows the predicted mean values for pH and moisture content. Low frequency PEF treatment (1, 20, and 50 Hz) had no effect on meat pH (P > 0.05). Changes in pH of meat after PEF treatment can be due to changes in the conductivity of meat after PEF treatment due to electroporation. Therefore, changes in pH became obvious when PEF treatment changed meat conductivity greatly especially with application of high electrical energy.

4.3.2. Changes in colour

In this study, colour parameters of lamb meat were significantly affected by the type of cut, storage, PEF processing and their interactions (Table 13). Colour parameters varied between chilled and frozen-thawed samples.

Table 13 Colour (L*, a*and b*) in chilled and frozen-thawed control and PEF treated lamb meat samples of different cuts at 0 and 7 days storage.

		Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Chilled	L	0	48.35axBC	44.35bC	53.807axA	46.29bBC	49.417B	48.62xB	50.35axAB	44.93byE	46.207axD	46.75bxD	53.18axA	48.45C	51.083B	41.247bF
		7	44.923ybB	45.32B	45.98yB	49.373A	49.137A	45.097ybB	44.94ayB	49.747axA	45.473yB	44.51yB	49.857yA	48.067A	48.687aA	41.483bC
	a	0	7.87bC	9.88axA	8.603BC	10.15axA	8.863bxB	9.353AB	9.443aAB	10.767aA	8.243bxC	9.073BC	8.507bxC	9.473aB	8.89BC	8.808bBC
		7	8.967aBC	9.28ayAB	8.343C	7.433ayD	7.23yD	9.163B	10.013aA	7.483bAB	7.883byAB	8.797A	6.517byB	7.197AB	8.697A	8.503bA
	b	0	10.377B	10.883B	12.607axA	10.517B	11xB	10.963bB	12.363axA	9.353C	11.523xB	11.123bxB	10.87xB	11.477xB	12.98axA	8.905bC
		7	9.887AB	10.283A	9.373byB	10.453aA	9.837yAB	10.483bA	10.293ayA	10.607B	10.037yBC	9.807ayBC	8.843byC	6.557yD	12.713ayA	8.977bC
Frozen-thawed	L	0	45.957C	49.1xAB	45.97C	47.39BC	50.657xA	50.78A	48.56aABC	45.657yD	49.26xAB	44.863yD	50.273yA	48.1BC	46.903CD	45.633byD
		7	45.757D	45.873yD	48.253C	48.337C	49.513yBC	50.853A	50.31AB	51.867xAB	44.99yD	49.747xC	53.057xA	50.283BC	45.373D	48.59xC
	a	0	8.243A	8.377axA	9.153axA	9.043axA	6.933yB	8.6A	6.83byB	8.29xAB	7.593bC	8.02xbBC	7.817bBC	8.84xA	8.013yBC	8.813axA
		7	8.56AB	8.063yB	7.313yC	8.567yA	8.433xAB	8.607A	7.083xC	7.02yC	7.68B	6.853yCD	6.907C	6.743yCD	8.633xA	6.517yD
	b	0	9.983B	10.813A	9.827B	10.977A	8.603yC	11.187A	8.947yC	10.217B	10.257B	10.013B	10.81AB	11.733A	10.693xAB	10.513xB
		7	10.38ABC	10.133BC	9.523C	10.327ABC	10.753xAB	11.143A	9.663xC	10.167AB	10.107AB	8.877BC	10.447A	11.08A	9.68yABC	8.617yC

a,b means with different letters show the significant effect of processing in each cut; x,y means with different letters in column show the significant effect of storage in each cut in same processing; A,B,C,D,E means with different letters in row show the significant effect of different cuts either with or without PEF processing using Fisher's least significant difference ($p < 0.05$).

The lightness (L*) values were significantly decreased ($p<0.05$) in non-PEF treated chilled (knuckle, rump shoulder and topside) and frozen-thawed (loin and shank) cuts with 7 days storage compared to corresponding 0 day storage samples. Aged meat contains free water that might increase the scattering coefficient resulting in lighter surface colour (Kim, Frandsen, & Rosenvold, 2011). The lightness (L*) of non-PEF treated chilled knuckle, rump and topside cuts as well as frozen-thawed topside cut significantly ($P < 0.05$) decreased after PEF processing. The decrease in colour indices (L*) may be due to increased sensitivity of meat to lipid oxidation, which resulted in increased oxidation of the myoglobin pigment (Ladeira et al., 2014). Furthermore, the decrease in lightness might be due to temperature increase induced by PEF treatment. O'Dowd et al (2013) reported that the L value was significantly higher in the control beef *M.semitendinosus* samples held at 5 °C compared to the PEF treated samples (1.9 $kV.cm^{-1}$; 250 pulses of 20 μs; 65 Hz; 83.6 kJ/kg), which induced an increase in temperature by 22 °C. Colour was less stable at elevated temperatures. In this study, PEF treatment induced an increase in temperature with an average of 10 °C for all chilled and frozen-thawed samples (see Table 12). However, only chilled (knuckle, rump and topside) and frozen-thawed (topside) cuts significantly decreased in lightness value after PEF processing. Hence we can postulate that decreased lightness of meat sample was more related to the oxidation of the myoglobin pigment rather than temperature change due to PEF processing.

Redness (a* values) significantly decreased ($P < 0.05$) in non-PEF treated chilled loin, rib and shank cuts and frozen-thawed loin, rump and rib cuts with 7 days storage compared to 0 day storage. Autoxidation can be accelerated and lipid-mediated myoglobin oxidation may occur during storage (Leygonie et al., 2012). The change in redness (a*) during storage can also be due to decreased metmyoglobin reducing activity (MRA), resulting in metmyoglobin accumulation in the meat surface (Utrera, Parra, & Estévez, 2014). It has been widely reported that redness in lamb decreased with vacuum and modified atmosphere storage (Camo, Beltrán, & Roncalés, 2008). The redness of non-PEF treated chilled loin, rib and topside cuts, and frozen-thawed loin, rump and rib cuts were significantly ($p<0.05$) higher than PEF treated samples of the same cuts. This may be due to the increased temperature generated from PEF processing that led to the higher oxidation of myoglobin to metmyoglobin resulting in decreased redness values. Similarly

low PEF (2.5 Kv, 200Hz and 20µs) intensity and non-PEF treated cold boned beef loin exhibited significant increased ($p<0.05$) redness compared to high intensity PEF (10 Kv, 200Hz and 20µs) processing (Khan et al., 2017).

With 7 days storage, the yellowness (b*) values were significantly decreased in non-PEF treated chilled rump, shank and topside cuts, and significantly increased in the frozen-thawed shank and topside cuts. Significantly lower yellowness (b*) values were found in PEF treated chilled rump and topside cuts compared to control. O'Dowd et al (2013) reported that the yellowness (b*) values were lower in PEF treated beef *semitendinosus* samples compared to control samples. This suggests that PEF treatment influenced the stability of oxymyoglobin. However, Arroyo et al (2015) found no significant difference for L*, a* and b* values between control and PEF treated (20 µs, 10 Hz, 300 and 600 pulses) beef *Longissimus thoracis et lumborum* muscle stored for 2, 10, 18 and 26 days compared to control.

4.3.3. Cooking loss

According to Lawrie & Ledward (2006), specific kinds of muscles have distinctive intrinsic moisture, protein and muscle fiber contents, which can influence the water holding capacity and total moisture content of each muscle. In this study, chilled and frozen-thawed non-PEF treated knuckle cut had higher ($p<0.05$) percentage of cooking loss, and shank cut had the least ($p<0.05$) cooking loss compared to other cuts (Table 14). Cooking loss (%) of chilled and frozen-thawed non-PEF treated shoulder was affected by storage ($P < 0.01$), which was mainly due to a significant increase in cooking loss of the samples stored for 7 days compared to 0 day. In contrast, cooking loss of chilled and frozen-thawed non-PEF treated rib cut decreased with increasing storage time. PEF treated chilled loin and shoulder cuts, and frozen-thawed rib cut at 0-day storage tended to have a higher ($p<0.05$) cooking loss than control samples. In contrast, PEF treated rump and shank cuts had significantly lower ($p<0.05$) cooking loss compared to non-PEF treated samples. PEF treated fresh beef loins (*Longissimus lumborum*) and topsides (*Semimembranosus*) at different voltages (5 and 10 kV) and frequencies (20, 50 and 90 Hz) with 3, 7, 14 and 21 days storage time also had lower cooking loss than non-PEF treated samples (Bekhit, van de Ven, Suwandy, Fahri, & Hopkins, 2014). In addition, different cooking loss results were observed for the same cuts with chilled and frozen-thawed as pre-treatments. Frozen-thawed knuckle, rump and shoulder cuts had less cooking loss (%) than chilled samples of the same cut. This may be explained by the fact that freezing and thawing alter both the distribution and content of moisture in meat tissue, and affect the amount of exudate. The exudate due to the melting of ice in the extracellular areas has been reported to result in the net flow of water into the intracellular areas (Leygonie et al., 2012).

Table 14 Cooking loss in chilled and frozen-thawed control and PEF treated samples of different cuts at 0 and 7 days storage

Pre-treatment	Storage	Control							PEF						
		Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Chilled	0	21.972A	12.376bE	20.042aB	15.188xD	11.571aF	15.132byD	18.536C	19.374xA	21.027aA	15.559byB	14.577B	8.434byC	21.079aA	19.293A
	7	20.081aA	13.704bD	18.694bBC	11.7966yE	13.638aD	19.321xAB	17.685C	15.948byB	19.58aA	19.121axA	14.157B	9.298xbC	20.639A	18.876A
Frozen-thawed	0	16.85BC	17.626XB	15.573yC	16.489bxBC	13.351D	13.919yD	19.594xA	17.432CD	18.424C	16.512D	23.537axA	11.627xE	10.513yE	19.76xB
	7	18.989A	14.293yCD	17.483xB	14.694yCD	13.849D	15.496xC	14.361yCD	18.708A	18.508A	18.297A	14.32yBC	9.857yD	15.198xB	13.406yC

a,b means with different letters show the significant effect of processing in each cut; x,y means with different letters in column show the significant effect of storage in each cut in same processing; A,B,C,D,E means with different letters in row show the significant effect of different cuts either with or without PEF processing using Fisher's least significant difference ($p < 0.05$).

4.3.4. Effect of PEF-induced changes on lipid oxidation during storage

4.3.3. Changes in lipid oxidation of chilled and frozen-thawed lamb meat

In this study, the level of lipid oxidation (TBARS value) in chilled and frozen-thawed lamb meat was measured (Table 15) to investigate the effect of storage and PEF treatment on meat oxidation.

MANOVA results showed that the lipid oxidation of lamb samples was significantly ($p<0.05$) affected by PEF storage, processing and different cuts. All four interactions (storage*processing, storage*cut, processing*storage and storage*processing*cut) were significant (data not are shown). Table 15 presents the development of lipid oxidation, as determined by MDA concentrations, in the chilled and frozen-thawed lamb meat determined after 0 and 7 days storage with non-PEF and PEF treatment.

Refrigerated storage increased the levels of MDA all chilled cuts regardless of non-PEF and PEF processing with a range between 0.09 mg MDA.kg^{-1} and 4.07 mg MDA.kg^{-1}, except non-PEF treated rib cuts and PEF treated topside cut. Regarding of frozen-thawed meat, no significant increasing of MDA level was found in non-PEF treated knuckle rump and topside cuts and PEF treated loin and shank cut with a range between 0.121 mg MDA.kg^{-1} and 1.047 mg MDA.kg^{-1}. Similarly Bekhit et al. (2014) reported that the lipid oxidation of beef loins and topsides were significantly increased during a storage period of 21 days. Faridnia et al (2015) demonstrated that the TBARS values of frozen-thawed PEF treated and control beef *semitendinosus* muscle samples after 18 days were significantly ($p< 0.05$) higher than sample stored for 6 days.

No significant PEF effect was shown in chilled loin, rib, and shoulder cuts at 0-day storage, whereas TBARS value of these chilled cuts was found significantly increased by PEF at 7 days storage. The consequences recommended that PEF processed chilled samples have been more inclined to oxidation at 7 days of storage. All PEF treated frozen-thawed meat cuts at 0 and 7 days storage had significant higher ($p<0.05$) MDA level than non-PEF treated samples with a range between 0.168 mg MDA.kg^{-1} and 1.016 mg MDA.kg^{-1}. Previous studies indicate that TBARS concentrations ranging from 0.6 up to 2.0 mg MDA. Kg^{-1} of muscle can lead to rancidity or off-flavor development in meat (Ponnampalam et al., 2014; Verma & Sahoo, 2000). Therefore, PEF processing significant ($p<0.05$) affected lipid oxidation in chilled and frozen-thawed meat, but

may not lead off-flavor in chilled meat. This may due to freezing and thawing meat cause the accelerated TBARS accumulation and the generation of pro-oxidants, especially the haem iron (Benjakul & Bauer, 2001). In addition, Leygonie, Britz, & Hoffman (2012) stated that remaining unfrozen water in frozen meat products can possibly induce primary lipid oxidation during frozen storage, and subsequently, secondary lipid oxidation occurs during thawing. Similarly, Akamittath, Brekke, & Schanus (1990) and Hansen, Lauridsen, Skibsted, Moawad, & Andersen (2004) reported that freezing-thawing could accelerate lipid oxidation during the shelf-life study.

The initial TBARS values (0 days) showed chilled non-PEF treated cuts (rib and shoulder) and PEF treated topside cut had the higher ($p<0.05$) TBARS level than another cut with same treated cuts. After 7 days, lipid oxidation of the chilled onion-PEF treated shoulder cut was significantly ($p<0.05$) higher compared to others, whereas PEF treated (rib and shoulder) cuts was significantly ($p<0.05$) higher compared to PEF treated (loin, shank, and knuckle) cuts. As regard frozen-thawed meat, the highest MDA level was found in knuckle cut with compare to others regardless storage and processing effects, whereas loin cut had lowest MDA level. Lipid oxidation, which is influenced by intramuscular fatty acid composition, particularly polyunsaturated fatty acids, leads to rapid quality deterioration and rancidity due to the production of volatile compounds that can strongly affect its aroma (Wood et al., 2008). Ladeira et al (2014) reported that higher oxidation levels were due to higher PUFA concentrations in young bulls fed with different diets. Badiani et al (2002) further reported that PUFA in beef shoulder was significantly ($p <0.05$) higher than rib cut.

Table 15 Lipid oxidation marker (TBARS) in chilled and frozen-thawed control and PEF treated lamb meat at 0 and 7 days storage for each cut

Pre-treatment	Storage	Control							PEF						
		Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Chilled	0	0.192byAB	0.164yCD	0.090byE	0.209A	0.173byBC	0.216yA	0.142byD	0.228ayB	0.199yB	0.251ayB	0.213yB	0.204ayB	0.211yB	0.334aA
	7	0.235bxB	0.220xbB	0.228bxB	0.228bB	0.201bxB	0.334bxA	0.249bxB	0.327axBC	0.304axCD	0.369axAB	0.407axA	0.285axD	0.401axA	0.369aAB
Frozen-thawed	0	0.453bA	0.168byCD	0.303bB	0.121byD	0.178byCD	0.126byD	0.240bC	0.562ayA	0.249aE	0.439ayCD	0.503ayB	0.490aC	0.344ayD	0.470ayC
	7	0.472bA	0.218bxD	0.386bB	0.460bxA	0.379bxB	0.284bxC	0.260bC	1.106axA	0.311aD	0.509axC	1.047axA	0.514aC	0.457axC	0.593axB

a,b means with different letters in row show significant effect of processing in each cut; x,y means with different letters in column show significant effect of storage in each cut in same processing; A,B,C,D,E means with different letters in row show significant effect of cut in each processing using Fisher's least significant difference ($p < 0.05$).

4.3.5. Changes in fatty acid profiles

Fatty acid composition can influence the sensory and nutritional quality of meat. The fatty acid composition present in different cuts of lamb meat with and without PEF treatment at 0 and 7 days storage is summarized in Tables 16 and 17. The most abundant fatty acids in all samples were palmitic acid (C16:0), stearic acid (C18:0), oleic acid (C18:1n9c) and linoleic (18:2n6). Lamb meat has been reported to have higher contents of C16:0, C18:0 and C18:1n9 fatty acids (Vasta et al., 2013). MANOVA results showed that the fatty acids of lamb samples were significantly ($p<0.05$) affected by storage, PEF processing and different cut types. All four interactions (storage*processing, storage*cut, processing*storage and storage*processing*cut) were significant (data not shown). Results in our study showed that PEF treatment significantly changed the fatty acid composition of meat, especially, n-6 or n-3 PUFA. These fatty acids are important to flavour development, as they produce a wide range of flavour precursors. Therefore, there appears to be a considerable change in fatty acid content of lamb meats with PEF processing. This has been reported to influence acceptability, healthiness and flavour (Wood & Enser, 1997).

Table 16 The fatty acids of chilled lamb cuts with and without PEF treatments (mg/100 g dry meat) during 0 or 7 days of storage

Fatty acids	Storage	Control							PEF						
		Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside	Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside
C16:1	0	0.772axB	0.376xF	0.255aG	0.823axA	0.496aE	0.695axC	0.588axD	0.575bxA	0.335bxE	0.217xF	0.547bxB	0.336bxE	0.478bxC	0.402bxD
	7	0.437ayB	0.183yF	0.213aE	0.588ayA	0.369aC	0.203ayEF	0.326ayD	0.246byB	0.161byCD	0.145yD	0.306byA	0.296byA	0.177byC	0.267byB
C18:1 cis-9	0	16.251axA	11.465axE	7.167xF	14.275axC	13.273axD	13.151xD	15.094axB	15.066bxA	9.629bxD	6.376xF	8.654bxE	8.545bxE	12.228xB	10.473bxC
	7	12.296ayA	6.466ayE	5.565yF	11.705ayB	9.54ayC	6.565ayE	8.308ayD	6.99byB	5.41byC	5.567yC	8.104byA	4.816byD	5.673byC	7.027byB
C18:2 (n-6)	0	4.576axA	3.349axC	3.98axB	3.966axB	3.915axB	3.905aB	2.865D	3.512xAB	2.76xD	3.34xB	3.06bxC	3.53bxA	3.393bxAB	2.739bD
	7	2.523ayC	2.606ayC	2.61ayC	3.358ayB	3.792ayA	3.174aB	2.651C	2.338yCD	2.011byE	2.217byDE	2.487byBC	2.932byA	2.604byB	2.62bB
C18:3 (n-3)	0	1.575axA	1.092axD	1.23axBC	1.27axBC	1.226axC	1.273aB	0.98axE	1.104bxA	0.919bxC	1.084bxA	0.961bxB	1.08bxA	0.906bxC	0.93bxBC
	7	0.794ayB	0.855aya	0.874ayB	1.133ayA	1.099ayA	0.861aB	0.836ayB	0.708byC	0.596byD	0.711byC	0.806byA	0.766byAB	0.733byBC	0.801byA
C20:1 (n-9)	0	0.03axCD	0.021axE	0.021axE	0.045aA	0.039axB	0.031axC	0.028axD	0.025bxAB	0.017bxCD	0.019bxC	0.023bxB	0.026bxA	0.024bxAB	0.016bD
	7	0.022ayB	0.014ayE	0.015ayD	0.027aB	0.034ayA	0.019ayD	0.012ayC	0.011byA	0.013byDE	0.01byE	0.013byCDE	0.013byAB	0.011byBCD	0.011bABC
C20:2 (n-6)	0	0.098axCD	0.087axD	0.103axBC	0.104axABC	0.11aABC	0.111aAB	0.116xA	0.095xBC	0.069xE	0.087xCD	0.078bxD	0.085bD	0.098bAB	0.105bxA
	7	0.089ayBC	0.067ayC	0.074ayABC	0.088ayA	0.1aAB	0.073aAB	0.078ayA	0.077byABC	0.064byABC	0.061byBC	0.068byC	0.075bAB	0.069bA	0.072byAB
C20:3 (n-6)	0	0.048axB	0.043axC	0.057axA	0.048aB	0.048axB	0.057aA	0.055xA	0.045xB	0.041xCD	0.047xA	0.039bxD	0.041bxC	0.047bxA	0.046bAB
	7	0.041ayF	0.04ayC	0.043yA	0.044E	0.043ayE	0.044aD	0.044ayB	0.039byC	0.038byC	0.036byA	0.035byD	0.04byC	0.041byB	0.04bA
C20:5 (n-3)	0	0.484axC	0.445axD	0.59axB	0.48axC	0.407axE	0.628aA	0.487axC	0.369bxE	0.411bxD	0.558bxA	0.291bxG	0.324bxF	0.451bxC	0.468bxB
	7	0.349ayC	0.395ayEF	0.473ayE	0.366ayB	0.363ayA	0.381aD	0.457ayF	0.288byC	0.303byAB	0.405byC	0.235byA	0.306byAB	0.365byC	0.415byBC
C14:0	0	0.784axA	0.411axD	0.572axB	0.426axD	0.318axE	0.487axC	0.429axD	0.443bxA	0.223bxD	0.34bB	0.286bxC	0.289bxC	0.265bxC	0.328bxB
	7	0.74ayA	0.375ayC	0.464yB	0.376ayC	0.261yE	0.346yD	0.364ayCD	0.385byA	0.217byE	0.282bB	0.263byC	0.24byD	0.193byF	0.287byB
C16:0	0	7.282axA	5.644axC	7.234axA	6.478axB	4.789axE	5.262axD	5.176axD	5.706bA	4.816bB	4.279bD	5.554xA	4.847xB	4.863xB	4.57xC
	7	6.695ayA	5.177ayB	6.861ayA	4.656ayC	4.507ayC	5.214ayB	4.881ayBC	4.566bBC	4.47bC	3.857bE	4.751byA	4.48byC	4.675byAB	4.049byD
C17:0	0	0.632axB	0.309axF	0.843axA	0.455axC	0.37axD	0.335axEF	0.337axE	0.409bxB	0.27bxD	0.455bxA	0.362bxC	0.265bxD	0.151bxF	0.209bxE
	7	0.431ayB	0.272ayD	0.552ayA	0.391ayC	0.24ayE	0.241ayE	0.277ayD	0.373byA	0.242byD	0.354byB	0.32byC	0.209byE	0.14byG	0.181byF

Fatty acids	Storage	Control							PEF						
		Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside	Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside
C18:0	0	6.553axA	5.395axCD	6.623axA	5.791axB	5.434axC	5.149axD	5.167xCD	4.494xBC	4.119byD	4.741bB	4.121bxD	6.055bxA	3.583xE	4.243xCD
	7	5.122yB	4.604yC	5.731ayA	5.683ayA	5.225ayB	4.623ayC	4.762ayC	4.363byB	3.779bxD	3.835bCD	3.832yCD	4.938yA	3.503byE	3.999byC
C20:0	0	0.226axB	0.163axD	0.276axA	0.202axC	0.194axC	0.128axE	0.1bxF	0.193aB	0.075bxE	0.205bxA	0.187bxB	0.148bxC	0.084bxD	0.083bxDE
	7	0.21ayB	0.094ayD	0.234ayA	0.211ayB	0.132ayC	0.091ayD	0.089yD	0.173A	0.065byC	0.177byA	0.132byB	0.09byC	0.073byC	0.066byC
C21:0	0	0.474aB	0.369axD	0.442xC	0.5xB	0.434ayC	0.561ayA	0.541axA	0.357bxD	0.321bE	0.532bA	0.346bxD	0.411bxC	0.447bxB	0.404bxC
	7	0.46aA	0.334ayE	0.401ayC	0.393ayCD	0.381axD	0.472axA	0.431yB	0.326yA	0.301bD	0.465bE	0.307yE	0.375yC	0.43byB	0.366byC
C22:0	0	0.048axA	0.028axD	0.039axB	0.032axC	0.032aC	0.028axD	0.025axE	0.021bxC	0.017bxDE	0.039bA	0.028bxB	0.029bxB	0.019bxD	0.016bxE
	7	0.03ayB	0.02ayDE	0.036ayA	0.024ayC	0.024aC	0.021ayD	0.018ayE	0.017byB	0.014yD	0.018B	0.015byC	0.028byA	0.017byB	0.011byE
C24:0	0	0.159axBC	0.165axB	0.127axE	0.145axD	0.155yC	0.163yB	0.186axA	0.131bxBC	0.109bxD	0.17bA	0.123xC	0.134xB	0.134bxB	0.14bxB
	7	0.14ayC	0.117ayE	0.126yD	0.117yE	0.124axDE	0.157axB	0.167ayA	0.121byB	0.105byD	0.133bA	0.101byD	0.116byC	0.114yC	0.129yA
SFA	0	16.158axA	12.485axD	16.156axE	14.028bxB	11.727axC	12.113aC	11.961axB	11.753bxA	9.951bxD	10.762bxF	11.008bxE	12.179bxE	9.547bxB	9.993bxC
	7	13.828ayA	10.992ayE	14.406ayF	11.852byB	10.893ayC	11.167aE	10.988ayD	10.325byB	9.194byC	9.121byC	9.722byA	10.477byD	9.143byC	9.087byB
MUFA	0	17.053axA	11.862axC	7.444axA	15.143axB	13.808axE	13.877axD	15.71axDE	15.665bxA	9.981bCD	6.612bB	9.224bxB	8.907bxA	12.73bxD	10.891bxC
	7	12.755ayB	6.662ayD	5.793ayA	12.32byC	9.943ayD	6.787ayD	8.647ayD	7.247byA	5.584bC	5.722bC	8.423byB	5.125byA	5.861byC	7.305byC
PUFA	0	6.782axA	5.015axC	5.96axB	5.868bxB	5.706axB	5.974aB	4.502xD	5.124xA	4.2bxD	5.116bxAB	4.43bxC	5.061bxAB	4.895bxB	4.287bCD
	7	3.796ayD	3.963ayD	4.073ayD	4.989byB	5.397ayA	4.533aC	4.067ayD	3.45byD	3.011byE	3.429byD	3.631byCD	4.119byA	3.812byBC	3.948bAB
P:S	0	0.42xBC	0.402axBC	0.369axD	0.418byBC	0.487axAB	0.493A	0.376bCD	0.436BC	0.422byC	0.475ayAB	0.402byD	0.416bxC	0.513xA	0.429aBC
	7	0.27y4D	0.361yC	0.283byD	0.421axB	0.495ayA	0.406B	0.37bC	0.334C	0.328bxD	0.376axBC	0.374bxBC	0.393byB	0.417yB	0.435aA
n-3	0	2.06axA	1.537axF	1.82axC	1.75bxD	1.634axE	1.902axB	1.467axG	1.472bxB	1.33bxD	1.642bxA	1.252bxE	1.405bxC	1.357bxCD	1.398bxC
	7	1.143ayD	1.251ayC	1.347ayB	1.499byA	1.462ayA	1.242ayC	1.294ayBC	0.996byD	0.899byE	1.116byB	1.041byCD	1.072byBC	1.098byB	1.216byA
n-6	0	4.723axA	3.478axC	4.14axB	4.118axB	4.072axB	4.073axB	3.035aD	3.651bxA	2.87bxD	3.474bxB	3.178bxC	3.656bA	3.538bxB	2.889bxD
	7	2.653yD	2.713ayCD	2.726ayC	3.491byB	3.935ayA	3.29ayB	2.773C	2.454yC	2.112byD	2.314byCD	2.59byBC	3.047bA	2.714yB	2.732yB
n-6/n-3	0	2.293axA	2.263axC	2.276axB	2.348bxB	2.493axB	2.142aB	2.07D	2.48xA	2.157xC	2.116xA	2.536bxB	2.603bxA	2.607bxA	2.066bC
	7	2.321ayC	2.169ayC	2.02ayC	2.329byB	2.692ayA	2.648aB	2.143C	2.464yCD	2.35byE	2.076byDE	2.481byBC	2.841byA	2.471byB	2.247bB
Total	0	39.993ax	29.362ax	29.559ax	35.039bx	31.241ax	31.965ax	32.173ax	32.542bx	24.132bx	22.49bx	24.661bx	26.147bx	27.172bx	25.172bx
	7	30.378ay	21.618ay	24.272ay	29.162by	26.233ay	22.486ay	23.702ay	21.022by	17.789by	18.272by	21.775by	19.722by	18.816by	20.341by

a,b means with different letters in row show the significant effect of processing in each cut; x,y means with different letters in column show the significant effect of storage in each cut in same processing; A,B,C,D,E means with different letters in row show the significant effect of different cuts either with or without PEF processing using Fisher's least significant difference ($p < 0.05$).

Table 17 The fatty acids of frozen-thawed lamb cuts with and without PEF treatments (mg/100 g dry meat) during 0 or 7 days of storage

Fatty acids	Storage	Control							PEF						
		Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside	Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside
C16:1	0	0.599axB	0.203axF	0.24aE	0.725axA	0.508axC	0.475axD	0.532axC	0.472bxA	0.122bxE	0.117bE	0.421bxB	0.324bxC	0.131bxE	0.299bxD
	7	0.489ayB	0.136ayG	0.168aF	0.634yA	0.449ayC	0.389ayD	0.351ayE	0.22byC	0.062byF	0.103bE	0.354yA	0.244byB	0.157byD	0.173byD
C18:1 cis-9	0	12.265axB	9.379axD	6.224aE	12.848axA	9.041axD	11.322axC	11.235axC	9.986bxA	8.247bxB	4.744bE	7.294bxC	6.395bxD	4.888bxE	7.128bxC
	7	10.606ayA	8.483ayC	5.786aF	7.789yD	6.845ayE	8.839ayB	5.307ayG	6.037byA	5.448byB	4.521bD	5.568yB	5.182byC	3.103byE	0.906byF
C18:2 (n-6)	0	4.483A	3.186xB	4.422aA	4.459axA	3.016axB	3.197xB	2.448axC	4.122xA	2.777xD	3.31C	3.77bxB	2.663bxD	2.523xD	1.952bxE
	7	4.559aA	3.251yC	3.309aC	4.075ayB	2.774ayD	2.583ayE	2.068ayF	3.287byB	2.644yC	2.418D	3.65byA	2.557byC	1.984byE	1.832byF
C18:3 (n-3)	0	1.551axA	0.828axF	0.956aD	1.027axC	1.133axB	0.876xE	0.671axG	0.705bxBC	0.675bxC	0.714bB	0.834bxA	0.69bxBC	0.391E	0.507bxD
	7	1.241ayA	0.731ayD	0.76aCD	0.917ayB	0.888ayBC	0.45yE	0.497ayE	0.617byCD	0.632byC	0.605bD	0.736byA	0.675byB	0.26F	0.467byE
C20:1 (n-9)	0	0.023axC	0.014axD	0.022aC	0.035xA	0.03axB	0.036axA	0.036axA	0.015bxCD	0.012byF	0.016bC	0.029xA	0.024bxB	0.014bxE	0.014bxDE
	7	0.017ayD	0.011yE	0.02aC	0.029yA	0.024yB	0.015ayD	0.016ayD	0.013byDE	0.012xE	0.014bC	0.024yA	0.017yB	0.013byCD	0.012byE
C20:2 (n-6)	0	0.091axB	0.086axC	0.095aA	0.084axC	0.093axAB	0.095xAB	0.096axA	0.079bxB	0.066bxD	0.015bE	0.075bxC	0.016bxE	0.075xC	0.084bxA
	7	0.082ayB	0.069ayC	0.087aA	0.079ayB	0.088yA	0.086yA	0.081ayB	0.012byE	0.063byB	0.012bE	0.053byC	0.012yE	0.072yA	0.016byD
C20:3 (n-6)	0	0.058axC	0.047axE	0.077aA	0.045axE	0.063axB	0.058xC	0.054xD	0.052bxAB	0.039bxE	0.057A	0.042bxDE	0.055bxA	0.046xCD	0.049xBC
	7	0.054ayC	0.042yE	0.067aA	0.044ayE	0.061ayB	0.054ayCD	0.051yD	0.047byAB	0.038yD	0.047AB	0.039byCD	0.049byA	0.042byC	0.045yB
C20:5 (n-3)	0	0.418xB	0.268axCD	0.591aA	0.221D	0.354axBC	0.379xBC	0.398axBC	0.268xCD	0.241bxCD	0.325bA	0.192xE	0.233bxD	0.275xBC	0.311bxAB
	7	0.325ayBC	0.257ayD	0.418aA	0.197E	0.319ayC	0.295yC	0.353yB	0.251byB	0.207byC	0.266bAB	0.164yD	0.238byB	0.175yD	0.287yA
C14:0	0	0.505axB	0.477axC	0.422aD	0.485axC	0.579axA	0.434xD	0.389xE	0.349bxC	0.327bxD	0.342bCD	0.419bxB	0.47bxA	0.31xE	0.284xF
	7	0.395yC	0.387yCD	0.388aC	0.431ayB	0.55ayA	0.382ayCD	0.368ayD	0.337yAB	0.312yB	0.309bB	0.357byA	0.362byA	0.271byC	0.255byC
C16:0	0	4.598axB	4.276axC	3.394aE	4.306axC	5.403axA	3.353axE	3.549axD	4.06bxB	3.621bxC	3.145bD	4.009bxB	4.333bxA	2.549bxF	2.898bxE
	7	4.307ayB	3.916ayD	3.264aE	4.171ayC	4.722ayA	2.862ayG	3.154yF	3.525byB	3.46byB	2.923bC	3.813byA	3.947byA	2.222byE	2.697yD
C17:0	0	0.432xC	0.38axD	0.371aD	0.632axA	0.546axB	0.346axE	0.324axF	0.362xC	0.268bxD	0.28bD	0.524bxA	0.443bxB	0.217bxE	0.206bxE
	7	0.413ayC	0.31yE	0.334aD	0.587yA	0.455ayB	0.287ayF	0.264byG	0.329byC	0.246yE	0.273bD	0.496yA	0.391byB	0.195byF	0.239ayE

Fatty acids	Storage	Control							PEF						
		Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside	Knuckle	Loin	Rib	Rump	Shank	Shoulder	Topside
C18:0	0	3.525axCD	3.261E	3.804aB	2.579axF	3.672axBC	4.098xA	3.34axDE	2.909bxC	3.275A	3.2bA	2.222bxD	2.952bxBC	3.163xAB	2.876bxC
	7	3.369ayAB	3.161aB	3.491aA	1.739yD	3.522ayA	3.609ayA	2.729ayC	2.548byBC	2.733bAB	2.819bA	1.411yD	2.446byC	2.862byA	2.377byC
C20:0	0	0.093axA	0.078axC	0.084aB	0.094axA	0.094axA	0.093axA	0.075axC	0.066bxBC	0.069bxB	0.065C	0.067bxBC	0.082bxA	0.058bxD	0.059bxD
	7	0.077yB	0.069ayC	0.068aC	0.079yB	0.086ayA	0.067ayC	0.062ayD	0.065yB	0.052byCD	0.063B	0.064yB	0.079byA	0.055byC	0.046byD
C21:0	0	0.357axCD	0.257E	0.438aA	0.244xE	0.405xB	0.369axC	0.345axD	0.301bxCD	0.236E	0.346bA	0.189xF	0.327xAB	0.281bxD	0.314bBC
	7	0.344ayBC	0.25aD	0.429aA	0.217yE	0.366yB	0.356ayB	0.323byC	0.266byC	0.216bD	0.287bB	0.178yE	0.277yBC	0.284byB	0.326aA
C22:0	0	0.039axBC	0.036aBC	0.039BC	0.03axC	0.047B	0.077A	0.07axA	0.026bxCD	0.032bC	0.016bD	0.025bxCD	0.032BC	0.058xA	0.045bxB
	7	0.032ayC	0.013aD	0.016D	0.027ayC	0.038C	0.065aA	0.053ayB	0.017byE	0.012bF	0.012bF	0.022byD	0.027C	0.055byA	0.042byB
C24:0	0	0.081xBCD	0.092xA	0.086aB	0.079axCDE	0.084axBC	0.074axE	0.077axDE	0.069xB	0.054xD	0.074bA	0.066bxC	0.073bxA	0.066bxC	0.067bxBC
	7	0.076yAB	0.08ayA	0.076aAB	0.07ayBC	0.076ayA	0.065yC	0.068ayC	0.069yA	0.046byD	0.062bB	0.062byB	0.072byA	0.058yC	0.058byC
SFA	0	9.63axB	8.858axD	8.638aE	8.449axA	10.831axD	8.844axC	8.167axC	8.143bxA	7.883bxB	7.468bE	7.521bxC	8.712bxD	6.702bxE	6.749bxC
	7	9.013ayA	8.184ayC	8.067aE	7.321yC	9.815ayD	7.694ayB	7.02ayE	7.155byA	7.076byC	6.748bD	6.405yB	7.6byC	6.003byE	6.039byF
MUFA	0	12.887axB	9.595axC	6.487aCD	13.608axD	9.579axA	11.833axC	11.802axE	10.474bxB	8.381bxC	4.876bD	7.743bxD	6.744bxA	5.033bxE	7.441bxE
	7	11.112ayB	8.63ayC	5.975aC	8.451ayE	7.318ayA	9.243ayD	5.673ayE	6.27byB	5.523byB	4.638bC	5.946byD	5.443byA	3.274byE	1.091byE
PUFA	0	6.601axA	4.416xC	6.14aAB	5.836axB	4.66axC	4.605axC	3.667axD	5.227bxA	3.798xC	4.42bB	4.913bxA	3.656bxC	3.31bxD	2.903bxE
	7	6.261ayA	4.35ayD	4.641aC	5.312ayB	4.13ayD	3.468yE	3.052ayF	4.214byB	3.584byC	3.349bD	4.642byA	3.532byC	2.533yE	2.647byE
P:S	0	0.685yB	0.498ayCD	0.711axA	0.691AB	0.43bxE	0.521xC	0.449D	0.643xA	0.482yBC	0.592bxAB	0.653yA	0.42ayD	0.494xB	0.43D
	7	0.695axB	0.532axC	0.575ayC	0.726A	0.421yE	0.451yD	0.435E	0.589byB	0.507xC	0.496byC	0.726xA	0.465xD	0.422yE	0.438E
n-3	0	1.97axA	1.096axD	1.546aB	1.247axC	1.487axB	1.255xC	1.069axD	0.973bxA	0.916bxBC	1.039bC	1.025bxAB	0.923bxC	0.666E	0.818bxD
	7	1.566ayA	0.988ayCD	1.178aB	1.114ayBC	1.207ayB	0.745yE	0.851ayDE	0.868byBC	0.838byC	0.872bABC	0.9byAB	0.913byA	0.435E	0.754byD
n-6	0	4.632A	3.319aBC	4.594axA	4.588aA	3.173aD	3.35B	2.598E	4.254xA	2.882bxC	3.381bxB	3.888bxB	2.734bC	2.644xC	2.085D
	7	4.695A	3.362C	3.463ayC	4.198aB	2.923D	2.722aD	2.201E	3.346yB	2.746yC	2.477byC	3.742byA	2.619D	2.098byE	1.893E
n-6/n-3	0	2.353A	3.028xB	2.973aA	3.678axA	2.135axB	2.672xB	2.428axC	4.371xA	3.146xD	3.278C	3.791bxB	2.963bxD	3.976xD	2.548bxE
	7	3.015aA	3.404yC	2.943aC	3.767ayB	2.465ayD	3.653ayE	2.587ayF	3.854byB	3.275yC	2.843E	4.158byA	2.874byD	4.82byF	2.511byG
Total	0	29.118ax	22.869ax	21.265ax	27.894ax	25.07ax	25.282ax	23.636ax	23.844bx	20.062bx	16.764b	20.177bx	19.112bx	15.045bx	17.093bx
	7	26.386ay	21.165ay	18.682ay	21.084ay	21.264ay	20.405ay	15.746ay	17.639by	16.183by	14.735b	16.992by	16.574by	11.809by	9.777by

a,b means with different letters in row show the significant effect of processing in each cut; x,y means with different letters in column show the significant effect of storage in each cut in same processing; A,B,C,D,E means with different letters in row show the significant effect of different cuts either with or without PEF processing using Fisher's least significant difference ($p < 0.05$).

Effect of Storage

A significant decrease in the content of total fatty acids, SFA, MUFA and PUFA in both chilled and frozen-thawed non-PEF treated meat cuts were observed with 7 days of refrigerated storage. Pereda, Ferragut, Quevedo, Guamis, & Trujillo (2008) demonstrated that the decrease in fatty acids can be a result of fatty acid oxidation and acidification. This is supported by our result that showed significantly higher ($P<0.05$) TBARS value in non-PEF treated meat samples after 7 days of storage compared to 0-day sample (see section 4.3.3). The oxidative stability of fatty acid composition in muscle is affected by processing, aging and retail display. PUFA in particular can be breakdown due to oxidation (Wood et al., 2008). The MUFA content in buffalo and turkey breast meat also decreased during storage (refrigerated and frozen), with a significant decrease in linoleic and oleic acids (Kesava Rao, Kowale, Babu, & Bisht, 1996; Salih, Price, Smith, & Dawson, 1989). In addition, the unsaturated fatty acids level (linolenic and palmitic acids) of ready-to-cook chicken dramatically decreased during frozen storage (Miteva & Bakalivanova, 1987). It can be concluded that the significant changes in fatty acids may affect the meat flavour. Wood et al (2004) reported that as storage time increased, the ability of unsaturated fatty acids to oxidize will play an important role in flavour development during cooking.

Effect of PEF Processing

PEF processing significantly ($p<0.05$) influenced the total SFA and MUFA content of all PEF treated chilled and frozen-thawed cuts. Similarly, SFA content of beef topside cut (*semitendinosus*) decreased after PEF, but not significantly (Faridnia et al., 2015). The individual SFA fatty acids in this study, C16:0 and C18:0 fatty acids, significantly decreased. This might be due to lipid metabolism induced by PEF. Stearoyl-CoA Desaturase enzyme (SCD) (also known as Δ^9-desaturase) is a critical enzyme that catalyzes the synthesis of monounsaturated fatty acids (Ntambi & Miyazaki, 2004), which can convert palmitic and stearic acids into C16:1 and C18:1 n9c, respectively (Conte, Jeronimo, Serra, Bessa, & Mele, 2012). The concentration of C16:1

and C18:1n9c fatty acids in all chilled and frozen-thawed meat cuts (except rib cut) significantly ($p<0.05$) decreased due to PEF processing. The decrease in fatty acids can be a result of fatty acid oxidation and acidification. PUFA content in chilled and frozen-thawed rib, rump and shank cuts, in particular linoleic acid (C18:2n6c) and alpha-linolenic acid (C18:3n3), significantly decreased after PEF processing as well. According to Wood et al (2008), the fatty acid content of muscle affects its oxidative stability, and PUFAs are more prone to oxidation than MUFA and SFA. In view of nutritional guidelines, Wood et al (2004) reported that the recommended ratio of PUFA to SFA (P:S) fatty acids in food should be above 0.4. The PUFA/SFA ratios in the present study ranged from 0.274 to 0.513 for all chilled samples, and from 0.42 to 0.695 for all frozen-thawed samples. PUFA/SFA ratio of *semitendinosus* muscle of Normand cows fed a weight-reduction plan supplemented with linseed or rapeseed ranged from 0.18 to 0.22 as reported by Habeanu et al (2014). It was also found in this study that PEF treatment significantly increased the PUFA/SFA ratio of chilled rib and topside cuts, and decrased the ratio of chilled shank and frozen-thawed rib cuts. Therefore, PEF treatment can significantly influence the nutritional value of lamb fatty acids in chilled rib and topside cut positively (with ratios above the recommended 0.4).

Effect of Different Cuts

In terms of different cuts, knuckle cut had significantly higher ($p<0.05$) amount of saturated fatty acids (SFA) (especially C16:0 and C18:0), monounsaturated fatty acids (MUFA) (C18:1n9c) and polyunsaturated fatty acids (PUFA) (C18:2n6c and C18:3n3) than rump, shoulder and topside cuts. According to Garcia et al (2008), Merino muscles (*Longissimus dorsi, Semitendinosus, Semimembranosus, Rectus femoris, Gluteus and Tensor fascia lata*) had significantly different oleic acid, alpha-linolenic acid (C18:3n3), PUFA, n-6 fatty acids and n-3 fatty acids content. Higher unsaturated fatty acid concentrations in meat can lead to problems related to shelf life and sensory characteristics, such as color and flavor (Ladeira et

al., 2014). The non-PEF treated frozen-thawed topside cut in this research had significantly lower PUFA/SFA ratio than knuckle cut. In contrast, Oriani et al (2005) found a higher PUFA/SFA ratio in the topside cut (*semimembranosus* muscle) compared to the knuckle cut (*quadriceps femoris*) of suckling lambs. Desimone et al (2013) further reported that Beef Alternative Merchandising (BAM) cuts (ribeye, top loin, sirloin) were not significantly different in linoleic acid content of the cooked meat. However, the linoleic acid content was significant higher in rib and rump cuts than in loin and topside cuts for, South African beef meat (Schönfeldt, Naudé, & Boshoff, 2010).

All these results show the PEF treatment significantly changed the fatty acid composition of meat, especially, n-6 polyunsaturated or n-3 polyunsaturated fatty acids. These fatty acids are important to flavour development as they produce a different range of flavour precursors. Therefore, there appears to be considerable scope to PEF treat lamb meat as it can influence the fatty acid content and potentially make it more acceptable to consumers in terms of both healthiness and flavor (Wood & Enser, 1997).

A multivariate study of fatty acids from different cuts of cooked lamb before and after PEF treatment after 0 and 7 days of storage

For the chilled and frozen-thawed meat data, separate Canonical Variate Analyses (CVA) was carried out on the fatty acids of non-PEF and PEF treated meat cuts at 0 and 7 days storage (Figure 23 and 24). Sample discrimination was explained by the first two canonical variates, which were 68.09 % for chilled meat data, and 73.5% for frozen-thawed meat data. MANOVAs were significant for both chilled meat ($F_{(432,303)}$ =224.663; $p < 0.0001$) and frozen-thawed meat ($F_{(432,303)}$ =244.856; $p < 0.0001$) data.

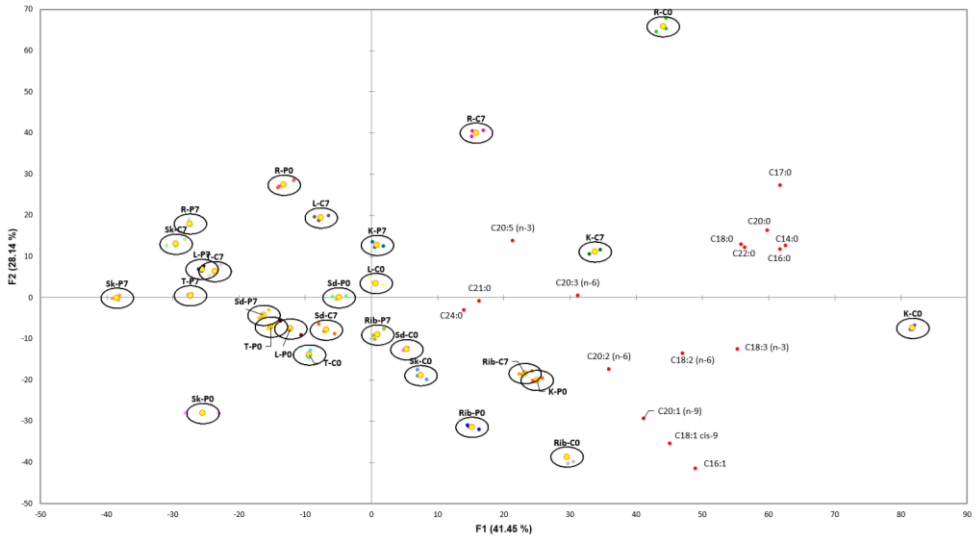

Figure 23 CVA Biplot of fatty acids for non-PEF and PEF treated chilled lamb meat with different cuts. Hotteling-Lawley MANOVA test showed significant product differences (F (432, 303) =224.663; $p < 0.0001$). Each point represents data from a single observer. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; Sk=Shank; T=Topside; C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage.

The CVA plot described 41.45% and 28.14% of the total variation of factor 1 (F1) and factor 2 (F2), respectively (Figure 23). Non-PEF treated knuckle cut at 0 day (K-C0) had high positive scores that corresponded to higher loadings of saturated fatty acids along F1. SFA (such as C16:0) and PUFA (such as C18:3 (n-3) and C18:2 (n-6)) were significantly higher ($p<0.05$) in non-PEF treated knuckle (K-C0) at 0-day storage (Table 16). Non-PEF treated rump, knuckle and rib cuts at 0 and 7 days had positive scores, and corresponded to higher loadings of all fatty acids. On the other hand, non-PEF treated loin, shoulder and shank cuts at 0 day had low positive values along F1. With 7

days storage, non-PEF treated loin, shoulder, shank and topside cuts corresponded to lower loadings of fatty acids. The individual SFA fatty acids in this study, C16:0 and C18:0 fatty acids, significantly decreased in these samples (Table 16). With PEF processing, 0 day samples had lower negative scores along F1 for shoulder, loin, topside, shank and rump cuts , while the 7 days stored samples had higher negative scores. The negative scores corresponded to lower loadings of fatty acids. This corresponded with results in Table 16 that showed the concentration of C16:1 and C18:1n9c fatty acids in most meat cuts significantly ($p<0.05$) decreased due to PEF processing.

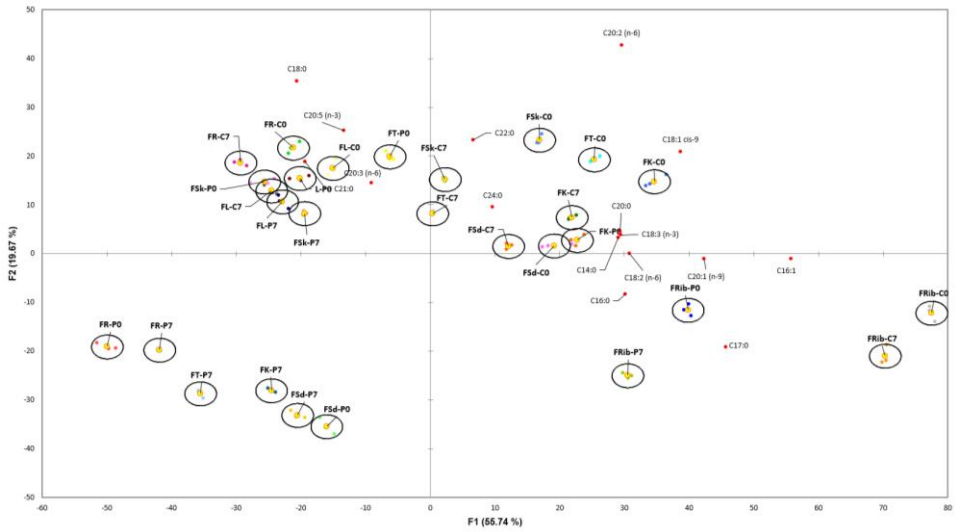

Figure 24 CVA Biplot of fatty acids for non-PEF and PEF treated frozen-thawed lamb meat of different cuts. Hotteling-Lawley MANOVA test showed significant product differences (F (432,303) =244.856; $p < 0.0001$). Each point represents data from a single observer. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; Sk=Shank; T=Topside; F:frozen C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage.

CVA plot of fatty acids for frozen-thawed meat shown in Fig 24 described 55.74% and 19.67% of the total variation of factor 1 (F1) and factor 2 (F2), respectively. It is clear that non-PEF treated topside, shank, shoulder, rib and knuckle cuts at 0 and 7 days had positive scores, which corresponded to higher loadings of most fatty acids, while almost all PEF treated cuts at 0 and 7 days had negative values along F1 except rib cuts (0 and 7 days) and knuckle (0 day only). The negative scores corresponded to lower loadings of fatty acids. This corresponded with results in Table 17 that showed the

concentration of fatty acids in most meat cuts significantly ($p<0.05$) decreased due to PEF processing. It was also found that almost all non-PEF treated cuts except rib cut at 0 and 7 days had positive scores that corresponded to higher loadings of most unsaturated fatty acids along F2, while almost all PEF treated samples except loin and shank cuts at 0 and 7 days had negative scores that corresponded to higher loadings of most saturated fatty acids along F2. These results indicated that PEF significantly affected the fatty acid profiles of of the different frozen-thawed cuts.

4.3.6. Changes in free amino acid profiles

A total of seventeen amino acids were given as mean values (mg/g dw) (Table 18 and 19). Cys and Arg were not reported in this study due to the limitation of the EZFaastTM amino acid analysis kit. FAAs can contribute to sweetness, bitterness, sourness or umami. In general, the three major amino acids were in control cut samples Ala, Gly, Asp and Phe. Gly, Ala, and Glu are the major free amino acids in goat (Madruga, Elmore, Oruna-Concha, Balagiannis, & Mottram, 2010) and cattle (Watanabe, Ueda, & HIGUCHI, 2004) meat. MANOVA results showed that the free amino acid content of lamb samples was significantly ($p<0.05$) influenced by PEF processing, storage, and the different type of cuts. All four interactions (storage*processing, storage*cut, processing*storage and storage*processing*cut) were significant (data not shown).

Table 18 The free amino acid composition of chilled lamb cuts with and without PEF treatments (mg/100 g dry meat) during 0 or 7 days of storage

Free amino acids		Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Essential amino acids	HIS	0	0.103byB	0.05byD	0.071byCD	0.102A	0.143yA	0.146yA	0.088byBC	0.144ayC	0.146ayC	0.17ayB	0.108yD	0.162BC	0.15yBC	0.238ayA
		7	0.135bxC	0.15bxBC	0.136bxC	0.112bC	0.197xAB	0.224xA	0.157bxBC	0.257axCD	0.213axD	0.331axB	0.193axD	0.193D	0.302xBC	0.421axA
	ILE	0	0.03byB	0.03byB	0.025byC	0.032AB	0.035byA	0.029byBC	0.03byB	0.065ayB	0.114aA	0.107aA	0.039yD	0.057ayBC	0.047ayCD	0.119ayA
		7	0.075bxA	0.086bxA	0.089bxA	0.037bB	0.051bxB	0.046bxB	0.075bxA	0.147axB	0.12aC	0.119aC	0.06axE	0.065axE	0.099axD	0.218axA
	LEU	0	0.137byA	0.098byC	0.1byC	0.116ABC	0.113byABC	0.131byAB	0.109byBC	0.266ayC	0.41aB	0.404ayB	0.127yE	0.187ayD	0.179ayD	0.486ayA
		7	0.235bxCD	0.328bxA	0.305bxAB	0.125bF	0.194bxDE	0.189bxE	0.271bxBC	0.69axB	0.433aD	0.507axC	0.24axF	0.282axE	0.413axD	0.961axA
	LYS	0	0.096A	0.025byD	0.037byC	0.065bB	0.065bB	0.065bB	0.045bC	0.095yC	0.129aB	0.129aB	0.095ayC	0.086aC	0.085ayC	0.142ayA
		7	0.079bA	0.049bxB	0.092bxA	0.072bA	0.075A	0.071bAB	0.049bB	0.269axB	0.124aCD	0.158aC	0.144axCD	0.086E	0.116axDE	0.409axA
	MET	0	0.079bAB	0.088A	0.069byBC	0.023bD	0.056byCD	0.05D	0.047byD	0.205aA	0.1yC	0.098ayC	0.05aE	0.081ayD	0.074yD	0.133ayB
		7	0.083bB	0.09bB	0.138xA	0.029bD	0.085bxB	0.058C	0.054bxC	0.231aA	0.262axA	0.185xB	0.057aD	0.139axC	0.18axBC	0.273axA
	PHE	0	0.213byB	0.102byE	0.114byDE	0.182yC	0.182byC	0.137byD	0.314aA	0.338ayB	0.407ayA	0.391ayA	0.208yD	0.328aB	0.335ayB	0.274byC
		7	0.358bxAB	0.37bxA	0.293bxC	0.284xBC	0.345xABC	0.292bxC	0.31bABC	0.708axB	0.598axC	0.614axC	0.331xE	0.342E	0.533axD	0.982axA
	THR	0	0.076bA	0.038byCD	0.03byD	0.059bB	0.043bC	0.058byB	0.048bBC	0.11ayB	0.091ayC	0.09ayC	0.078ayC	0.088aC	0.114ayB	0.145ayA
		7	0.068bAB	0.068bxAB	0.077axAB	0.062bAB	0.046bC	0.087bxA	0.058bBC	0.171axB	0.144axC	0.143axC	0.096axD	0.097aD	0.176axB	0.221axA
	VAL	0	0.072byB	0.057byD	0.06byCD	0.069B	0.103byA	0.069byBC	0.075byB	0.104ayD	0.188aA	0.153aB	0.053yE	0.133ayC	0.093ayD	0.196ayA
		7	0.133bxB	0.141bxAB	0.145bxAB	0.075bC	0.164xA	0.099bxC	0.131bxB	0.221axB	0.199aC	0.161aD	0.128axE	0.164xD	0.155axD	0.325axA

Free amino acids		Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Non-essential amino acids	ASP	0	0.237byB	0.154byC	0.21byBC	0.156byC	0.02byD	0.189bBC	0.296byA	0.566aA	0.333ayD	0.475ayC	0.377ayD	0.538aAB	0.475aC	0.486aBC
		7	0.437xA	0.357bxAB	0.367bxAB	0.291bxA	0.183bxC	0.23bBC	0.391bxA	0.489BC	0.449axC	0.579axA	0.596axA	0.564aAB	0.518aABC	0.525aABC
	GLU	0	0.086bA	0.037byC	0.054bB	0.067B	0.017byD	0.021byD	0.064bB	0.116ayA	0.066ayC	0.068ayC	0.067yC	0.094ayB	0.086aB	0.095ayB
		7	0.1A	0.064bxCD	0.045bD	0.067bBC	0.098xAB	0.062bxCD	0.054bD	0.122xB	0.077axD	0.14axA	0.1axC	0.118xB	0.095aC	0.124axAB
	TRP	0	0.027bB	0.009ayD	0.015byBC	0.022byC	0.028byB	0.006byD	0.055bA	0.034ayC	0.04byC	0.066ayA	0.034ayC	0.06ayAB	0.02aD	0.064ayB
		7	0.024bC	0.037bxB	0.024bxD	0.035bxB	0.037bxB	0.016bxD	0.055bA	0.08axC	0.047axB	0.137axD	0.044axB	0.071axB	0.023aD	0.089axA
	TYR	0	0.123bC	0.069byD	0.075byD	0.048byD	0.204byB	0.071byD	0.066byA	0.243ayA	0.167ayB	0.238ayA	0.107aC	0.246aA	0.148aB	0.402ayD
		7	0.104bD	0.216bxA	0.172bxB	0.072bxE	0.229bxA	0.12xCD	0.136bxC	0.544axAB	0.455axB	0.593axA	0.125aD	0.254aC	0.132D	0.55axAB
	ALA	0	0.871B	0.605C	0.834yB	0.667bC	0.598yC	0.992byA	0.65bC	0.905yC	0.686yD	0.895B	1.139aA	0.669yD	1.15aA	0.928ayBC
		7	0.916bABC	0.73bCD	0.992xAB	0.691bBC	0.879xBC	1.143xA	0.569bD	1.254axA	0.902axC	1.006CD	1.183aB	0.832xD	1.243AB	1.25axAB
	GLY	0	0.213bB	0.17byC	0.17byC	0.196byB	0.219byAB	0.239bA	0.214bB	0.394ayB	0.233ayD	0.247ayD	0.295ayC	0.291ayC	0.319ayC	0.433aA
		7	0.198bB	0.227bxAB	0.216bxAB	0.234bxA	0.265bxA	0.269bA	0.197bB	0.443axBC	0.437axBC	0.458axB	0.378axCD	0.363axD	0.539axA	0.465aB
	PRO	0	0.082bAB	0.059bC	0.059byC	0.082bAB	0.082byAB	0.086byA	0.07byBC	0.113ayD	0.086ayF	0.089ayF	0.1ayE	0.132aC	0.15ayB	0.177ayA
		7	0.081bC	0.093bBC	0.079bxC	0.076bBC	0.125xAB	0.152bxA	0.099bxBC	0.195axBC	0.219axB	0.19axBC	0.142axC	0.145C	0.338axA	0.384axA
	SER	0	0.029byAB	0.028byAB	0.003byD	0.028byB	0.027byB	0.033byA	0.01byC	0.055ayCD	0.077aBC	0.06ayBCD	0.058ayA	0.04aD	0.051ayD	0.082ayB
		7	0.074bxB	0.069xB	0.105xA	0.049bxC	0.034bxD	0.099xA	0.042bxCD	0.104axC	0.077D	0.098xC	0.175axDE	0.049aE	0.124xB	0.147axA
Total		0	2.466byAB	1.619byD	1.936byC	1.968bC	1.935byC	2.336byB	2.525bA	3.754ayB	3.28ayCD	3.797ayAB	3.024ayD	3.191ayD	3.478ayC	4.055ayA
		7	3.100bxB	3.092bxCD	3.268bxAB	2.305bD	3.364bxA	3.158bxC	2.649bD	5.926axB	4.751axD	5.303axC	3.876axE	3.762axE	4.985axCD	7.343axA

a,b means with different letters in row show the significant effect of processing in each cut; x,y means with different letters in column show the significant effect of storage in each cut in same processing; A,B,C,D,E means with different letters in row show the significant effect of different cuts either with or without PEF processing using Fisher's least significant difference ($p < 0.05$).

Table 19 The free amino acid composition of *frozen-thawed* lamb cuts with and without PEF treatments (mg/100 g dry meat) during 0 or 7 days of storage

Free amino acids		Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Essential amino acids	HIS	0	0.137bBC	0.11yDE	0.189A	0.088yE	0.086byE	0.163bAB	0.116byCD	0.292ayA	0.124yB	0.202yA	0.144A	0.158ayA	0.184ayA	0.158ayA
		7	0.16bA	0.203bxD	0.205bB	0.198xCD	0.205bxBCD	0.219bBC	0.219bxBCD	0.459axB	0.442axB	0.61axA	0.232D	0.368axBC	0.346axBCD	0.324axCD
	ILE	0	0.062byB	0.043byC	0.089yA	0.044byC	0.027byD	0.065yB	0.07byB	0.191aC	0.07ayB	0.099yB	0.058ayD	0.042ayD	0.068yB	0.1ayA
		7	0.125bxA	0.177xC	0.176bxB	0.109xC	0.11bxD	0.165bxC	0.209bxB	0.2aCD	0.202xCD	0.312axA	0.099xE	0.173axD	0.217axBC	0.246axB
	LEU	0	0.218byD	0.224byD	0.384byA	0.15bE	0.135byE	0.258byC	0.342byB	0.273ayA	0.362ayB	0.508ayA	0.178ayC	0.19ayC	0.341ayC	0.402ayAB
		7	0.988xD	0.797bxC	0.992bxA	0.338E	0.497bxE	0.466bxC	0.965bxB	1.002xC	0.946axC	1.368axA	0.378xE	0.785axD	0.78axD	1.256axB
	LYS	0	0.096yBC	0.073yCD	0.066byD	0.017byE	0.052byD	0.122yA	0.114byAB	0.069yA	0.095yB	0.206ayA	0.075aC	0.069ayC	0.126yC	0.141ayA
		7	0.339xD	0.257xCD	0.329axA	0.166xD	0.17bxD	0.174bxBC	0.336bxB	0.292xB	0.288xB	0.366axA	0.115D	0.239axC	0.287axB	0.402axA
	MET	0	0.107yC	0.122yBC	0.162byA	0.04byE	0.072byD	0.139yB	0.063byDE	0.106yA	0.152yC	0.227ayB	0.11aF	0.147ayE	0.166D	0.114ayC
		7	0.326xA	0.255xC	0.292bxB	0.08BxC	0.139bxB	0.211xB	0.259bxC	0.333xB	0.254xC	0.458axA	0.122aD	0.274axBC	0.228C	0.457axA
	PHE	0	0.352yBC	0.308byC	0.41yAB	0.23byD	0.217byD	0.453A	0.309byC	0.362yA	0.378ayAB	0.507yAB	0.295ayD	0.329ayC	0.508yC	0.427ayB
		7	0.894xCD	0.851xC	0.88bxA	0.347bxE	0.526bxDE	0.471bA	0.838bxB	0.91xD	0.961axCD	1.645axA	0.581axF	1.048axBC	0.793axE	1.108axB
	THR	0	0.072yAB	0.056yC	0.075byA	0.068AB	0.033byD	0.069yAB	0.062byBC	0.068yA	0.073yAB	0.094ayAB	0.087yC	0.07ayC	0.079yB	0.1ayAB
		7	0.183bxC	0.157axBC	0.159bxA	0.09bAB	0.101bxC	0.146bxBC	0.161bxA	0.212axAB	0.195axB	0.237axA	0.145axC	0.193axB	0.232axA	0.235axA
	VAL	0	0.07yCD	0.075byC	0.104yA	0.078yBC	0.054byD	0.087ABC	0.096byAB	0.071yA	0.127ayA	0.118yA	0.075yB	0.075ayB	0.107yC	0.133ayA
		7	0.246bxC	0.254axA	0.235bxAB	0.149bxC	0.169bxC	0.096bB	0.248bxA	0.314axAB	0.3axABC	0.315axAB	0.192axD	0.271axC	0.29axBC	0.331axA

Free amino acids		Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Non-essential amino acids	ASP	0	0.075byC	0.123bA	0.083byBC	0.116bA	0.059byCD	0.034byD	0.106AB	0.184ayA	0.194aBC	0.172ayBCD	0.179ayA	0.158ayCD	0.158ayB	0.133D
		7	0.137bxBC	0.148bA	0.126bxAB	0.211bA	0.106bxABC	0.151bxABC	0.103bC	0.254axC	0.253aB	0.199axC	0.941axA	0.183axC	0.262axB	0.166aC
	GLU	0	0.059byB	0.051bBC	0.047byC	0.023byD	0.029byD	0.092bA	0.044byC	0.122aA	0.083aC	0.096ayBC	0.083ayB	0.089aB	0.102ayB	0.064aBC
		7	0.11xA	0.054BC	0.071bxB	0.08bxBC	0.077xBC	0.079bAB	0.066xC	0.135B	0.059D	0.142axB	0.133axBC	0.109C	0.195axA	0.076D
	TRP	0	0.055byB	0.026byD	0.028byD	0.062A	0.056byB	0.036bC	0.016byE	0.078ayA	0.079aD	0.11ayD	0.07C	0.075ayC	0.042ayD	0.036ayB
		7	0.137xB	0.044bxB	0.038bxA	0.07B	0.084bxB	0.037bC	0.11bxC	0.135xCD	0.092aEF	0.387axA	0.078F	0.162axBC	0.111axDE	0.176axB
	TYR	0	0.236yB	0.233yB	0.327ayA	0.176yC	0.116byD	0.235yB	0.213byBC	0.237yC	0.286yC	0.354ayA	0.215yE	0.222ayD	0.246yDE	0.262ayB
		7	0.493bxCD	0.49bxB	0.688bxA	0.317xD	0.392bxCD	0.363bxBCD	0.596bxBC	0.772axC	0.964axB	1.411axA	0.345xE	0.694axC	0.557axD	0.79axC
	ALA	0	0.646byAB	0.548yC	0.551byC	0.323byD	0.532byC	0.58byBC	0.724byA	0.866ayA	0.652yB	0.967ayA	0.597ayC	0.726ayBC	1.066aBC	0.895ayA
		7	1.189bxB	0.919bxC	1.195bxAB	0.762bxC	0.804bxC	0.846bxA	1.177bxB	1.327axA	1.104axB	1.355axA	0.905axC	1.12axB	1.337aA	1.343axA
	GLY	0	0.235byB	0.276A	0.209byBC	0.174byD	0.217byB	0.185byCD	0.185byCD	0.363ayA	0.266yA	0.259ayB	0.238ayB	0.314ayB	0.346aB	0.318ayB
		7	0.413xA	0.416aC	0.269bxC	0.236bxC	0.291bxB	0.255bxAB	0.294bxB	0.497xABC	0.476axBCD	0.548axA	0.331axE	0.532axAB	0.426aD	0.449axCD
	PRO	0	0.083byAB	0.075yBC	0.079yBC	0.065yCD	0.058byD	0.097byA	0.054byD	0.149ayB	0.086yD	0.11yD	0.078yB	0.103ayA	0.113ayC	0.088ayD
		7	0.175bxA	0.106bxCD	0.107bxB	0.162bxD	0.248bxBC	0.132bxB	0.113bxCD	0.417axA	0.346axABC	0.367axAB	0.267axCD	0.417axA	0.293axBCD	0.2axD
	SER	0	0.035byAB	0.041byA	0.039byA	0.017byD	0.021yCD	0.029bBC	0.029byB	0.109ayA	0.053ayB	0.081ayB	0.035ayC	0.025yB	0.078ayD	0.06aB
		7	0.156xA	0.118axC	0.11bxB	0.073xD	0.101bxD	0.036bB	0.12xC	0.156xA	0.117axAB	0.179axAB	0.108xB	0.162axAB	0.163axAB	0.125AB
Total		0	2.541byBC	2.385byC	2.843byA	1.67byD	1.765byD	2.646byAB	2.543byBC	3.492ayB	3.079ayC	4.11ayA	2.517ayD	2.791ayC	3.731ayB	3.431ayB
		7	6.2187bxA	5.246bxD	5.872bxBC	3.389bxE	4.019bxDE	3.898bxB	5.813bxC	7.194axBC	7.000axCD	9.9axA	4.972axE	6.653xCD	6.5465axD	7.684axB

a,b means with different letters in row show the significant effect of processing in each cut; x,y means with different letters in column show the significant effect of storage in each cut in same processing; A,B,C,D,E means with different letters in row show the significant effect of different cuts either with or without PEF processing using Fisher's least significant difference ($p < 0.05$).

Effect of Storage

A significant increase in the content of total FAA in non-PEF treated chilled and frozen-thawed meat cuts (except for chilled rib and topside cuts) was observed after 7 days storage. It was also found that total concentration of free amino acids significantly increased ($p<0.05$) by almost 2-fold in non-PEF treated chilled loin cut and almost all frozen-thawed cuts (except for shoulder cut). An increase in amino acid content in beef during the aging period has been reported by Toldrá (2006). Proteolysis may have contributed to the breakdown of myofibrillar protein, and the calpains and cathepsins acting on myofibrillar proteins, which may generate protein fragments and polypeptides (Huff Lonergan et al., 2010). The polypeptides and peptides may further generate free amino acids during storage of meat. In terms of essential free amino acids, His, Ile, Leu and Val content were significantly increased in all non-PEF treated chilled and frozen-thawed cuts (except chilled rib cut) after 7 days storage. Val and Phe however increased significantly during 7 days of storage in non-PEF treated chilled (especially loin, rump, shank and shoulder) and frozen-thawed (except for shoulder) meat cuts.

In terms of non-essential free amino acids, Glu, Asp, and Trp increased significantly during 7 days of storage in non-PEF treated chilled (especially loin, rump, shank and shoulder) and frozen-thawed (especially knuckle, rump shank and topside) meat cuts. Increases in free amino acids with different cuts may be related to troponin-T degradation. Marino, Della Malva, & Albenzio (2015) stated that troponin-T degradation of podolian bull *semitendinosus* and *longissimus* had different proteolytic potential during storage. During aging, free amino acids of beef meat was found to significantly ($p<0.05$) increase, especially Phe, Met, Lys, Leu and Ile content (Koutsidis et al., 2008).

Effect of PEF processing

With PEF treatment, total FAA content significantly increased ($p< 0.05$) in both chilled and frozen-thawed lamb meats cut at 0 storage. This increase in free amino acids might be attributed to degradation of proteins due to proteolysis induced by PEF processing. PEF can contribute to the myofibril degradation that result in the release of protease enzymes from the lysosomes and potentially accelerate the release of Ca^{2+} ions. This can lead to activation of the calcium-activated

protease μ-calpain early postmortem and stimulate the glycolysis process that is required for accelerated proteolysis (Bekhit, van de Ven, et al., 2014). The increase in total free amino acids was higher in PEF treated chilled topside and knuckle cuts, and frozen-thawed rump and shoulder cuts stored for 7 days compared to the non-PEF treated samples of the corresponding cuts. This result may suggest increased tenderizing effect with PEF treatments of these cuts. The combination of PEF treatment with aging has been reported to increase the rate of proteolysis that can result in further meat tenderization (Faridnia et al., 2015).

Effect of Different Cuts

A significant difference in total free amino acids was also found between the different cuts. For chilled meat, the highest values ($p<0.05$) of total free amino acids was found in non-PEF (0-day storage) and PEF treated topside cut (0 and 7 days storage), and non-PEF treated shank cut at 7 days storage compared to other cuts (Table 18).

As for frozen cuts, the highest values ($p<0.05$) of total free amino acids was found in non-PEF (0-day storage) and PEF treated rump cut (0 and 7 days storage), and non-PEF treated knuckle cut at 7 days storage compared to other cuts (Table 19). Oh et al (2016) examined the free amino acids content of six different cuts (loin, tenderloin, rib, brisket, topside and shank) of Hanwoo beef. They found significantly higher ($p<0.05$) level of free amino acids in the topside cut compared to rib, loin and tenderloin cuts. In contrast, the total free amino acids content was significantly higher ($p<0.05$) in loin compared to round (topside) beef cut (Wu et al., 2016).

In this study, the content of essential amino acids, Val, His and Phe, were significantly higher ($p < 0.05$) in non-PEF treated shank and topside cuts than rib and loin cuts at 0-day. Oh et al (2016) also reported that Val and Phe content were higher in brisket, topside and shank cuts compared to loin, tenderloin and rib cuts. Conversely, methionine content was higher in rib and loin cuts than shank and topside cuts. Methionine is an important precursor of sulphur volatile compounds meat (Mottram, 1998). Feidt, Petit, Bruas-Reignier, & Brun-Bellut (1996) concluded that different enzyme activities are modulated by inhibitors, like calpastatin for calpains or like cystatins for lysosomal cathepsins that can result in release of amino-acids that vary with M.*longissimus dorsi*, M. *triceps brachii* and M.*rectus femoris* muscles in bovine meat.

A multivariate study of free amino acids from different cuts of cooked lamb before and after PEF treatments after 0 and 7 days of storage

For the chilled and frozen-thawed meat data, separate Canonical Variate Analyses (CVA) was carried out on the free amino acids of non-PEF and PEF treated meat cut at 0 and 7 days storage (Fig. 25 and 26). Sample discrimination was explained by the first two canonical variates, which were 68.09 % for chilled meat data, and 73.5% for frozen-thawed meat data. MANOVAs were significant for both chilled meat ($F_{(456,302)}$ =962.57; $p < 0.0001$) and frozen-thawed meat ($F_{(456,302)}$ =771.786; $p < 0.0001$).

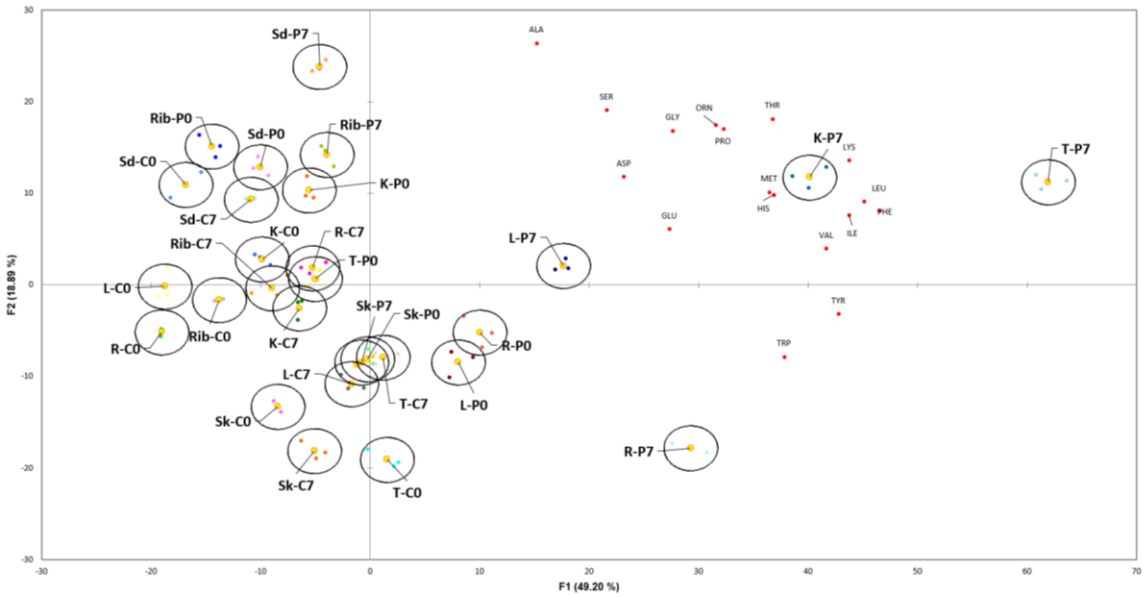

Figure 25 CVA Biplot of free amino acids for non-PEF and PEF treated chilled lamb meat of different cuts. Hotteling-Lawley MANOVA test showed significant product differences (F (456,302) =962.57; $p < 0.0001$) based on free amino acids. Each point represents data from a single observer. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; Sk=Shank; T=Topside; C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage.

CVA plot of free amino acids for chilled meat shown in Fig 25 described 49.20% and 18.89% of the total variation of factor 1 (F1) and factor 2 (F2), respectively. PEF treated knuckle and topside cuts at 7-day storage (K-P7 and T-P7) had the highest positive scores that corresponded to higher loadings of free amino acids. Phe, Lys, Leu. Ile, His and Val were significantly higher ($p<0.05$) in PEF treated knuckle (K-P7) and topside (T-P7) at 7-day storage (Table 18). Faridnia et al (2015)

reported that combined PEF and aging further increased beef *semitendinosus* (ST) meat tenderization due to increased proteolysis. PEF treated rump and loin cuts at 0 days (R-P0 and L-P0) had low positive scores that increased after 7 days storage (R-P7 and L-P7) with medium positive scores along F1. This result is supported by findings in the current study that showed Trp, Tyr, Glu, Lys, Met, His, Val, Ile and Pro were significantly higher ($p<0.05$) in PEF treated rump (R-P7) and loin (L-P7) at 7 days storage compared to PEF treated rump (R-P0) and loin (L-P0) cuts at 0 day storage samples (Table 18). Almost all non-PEF treated meat cuts except for topside cut at 0 and 7 days storage had negative scores that corresponded to lower loadings of free amino acids along F1. This result is supported by findings in the current study that showed total free amino acids content were significantly lower ($p<0.05$) in all non-PEF treated meat cuts at 0 and 7 days storage compared to all PEF treated meat at 0 day and 7 days storage samples (Table 18).

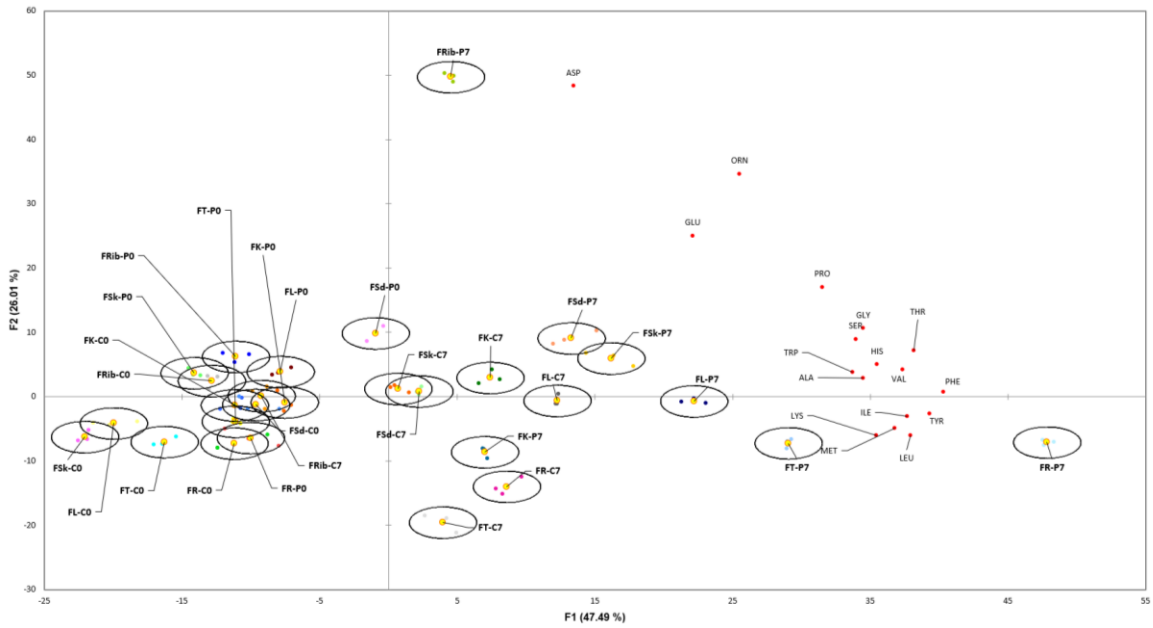

Figure 26 CVA Biplot of free amino acids for non-PEF and PEF treated frozen-thawed lamb meat of different cuts. Hotteling-Lawley MANOVA test showed significant product differences ($F(459,302) = 771.786$; $p < 0.0001$) based on free amino acids. Each point represents data from a single observer. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; Sk=Shank; T=Topside; F: frozen; C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage

CVA plot of free amino acids for frozen-thawed meat shown in Fig 26 described 47.49% and 26.01% of the explained by F1 and F2 respectively. It is clear that almost all samples of the different meat cuts (except rib cut) stored for 7 days had positive scores, which corresponded to

higher loadings of free amino acids. In fact, the PEF treated samples stored for 7 days had higher scores than the corresponding non-PEF treated samples stored for 7 days. In fact, Thr, Val, Asp, Ala and Pro content were significantly higher ($p<0.05$) in PEF treated samples stored for 7 days compared to non-PEF treated samples stored for 7 days (Table 19). PEF treated rump cut at 7 days (R-P7) had the highest positive scores that corresponded to the highest loadings of free aminos along F1. Results from this study also showed that Phe, Lys, Leu. Ile, His and Val content were significantly higher ($p<0.05$) in PEF treated rump (FR-P7) at 7 days storage compared to other PEF treated cuts at 7 days storage (Table 19).

The PEF and non-PEF treated samples at 0 day on the other hand had negative scores along F1. This result is supported by findings in the current study that showed total free amino acids content were significantly lower ($p<0.05$) in all PEF and non-PEF treated samples at 0 day storage compared to all PEF and non-PEF treated samples at 7 days storage samples (Table 19). These results in this study indicated that storage mainly contributed to the increase in levels of free amino acids and when combined with PEF treatments further increased amino acids content that could be attributed to proteolysis. Freezing and thawing samples can damage the membrane of the muscle cells which induce the release of mitochondrial and lysosomal enzymes, and finally contribute to the increase in proteolysis (Leygonie et al., 2012). This will impact the water fraction of meat, and influences meat conductivity. In this study, higher electrical conductivities were found in frozen-thawed meat, which may result in reduce the effects of PEF. The high electrical conductivities of meat products may limit the electric field strength that can be used (Alahakoon et al., 2016).

4.3.7. Conclusion

It is obvious that PEF significantly affected physicochemical properties and sensory characteristics of the seven lamb meat cuts. There were less PEF effects on cooking loss when applied to frozen-thawed meat compared to chilled meat samples. With chilled lamb cuts, storage and PEF processing influenced the fatty acids profile of the different cuts. However with frozen-thawed cuts, only PEF influenced the fatty acids profile. For chilled meat, PEF treatment

influenced the free amino acids profiles of rump, loin and rib. With frozen-thawed meat, free amino acids increased with increased storage time. These findings clearly indicate that PEF and freezing affected lipid oxidation, as well as fatty acids and free amino acids profiles of lamb meat. Hence effects of PEF processing on flavour and aroma are necessary. Further changes in the temporal sensory attributes of PEF processed meat was further carried out in section 4.4.

4.4. The impact of pulsed electric field (PEF) on volatile profile and sensory attributes of chilled and frozen-thawed lamb meat with seven different cuts

Consumers demand lamb meat that is lean and palatable with good nutritional attributes. These three key drivers influence the purchase and "willingness to pay" decisions of consumers (Pethick, Banks, Hales, & Ross, 2006). Pulsed electric field (PEF) technology is a nonthermal processing method with low energy requirements that minimizes quality deterioration of food. PEF is an emerging food processing technology,which has beenwidely investigated in terms of its potential for industrial pasteurization of liquid food such as beer, fruit juice and milk (Bermúdez-Aguirre, Fernández, Esquivel, Dunne, & Barbosa-Cánovas, 2011; Milani, Alkhafaji, & Silva, 2015; Timmermans et al., 2014).

Recently, extensive studies have been conducted on muscle foods. It has been reported that the use of PEF in muscle foods (especially in beef) can enhance cell permeability due to electroporation and consequently enhance proteolysis that contributes to tenderisation (Bekhit, van de Ven, Suwandy, Fahri, & Hopkins, 2014; Suwandy, Carne, van de Ven, Bekhit, & Hopkins, 2015; Jaeger, Balasa, & Knorr, 2008; Toepfl, Heinz, & Knorr, 2007). Lopp & Weber (2005) reported that PEF treatment (3.5 kV·cm−1, 20 Hz, 5 s) enhanced tenderness of beef triceps brachii muscles. However in another research (O'Dowd, Arimi, Noci, Cronin, & Lyng, 2013), PEF treatments (1.1–2.8 $kV \cdot cm^{-1}$, 5–200 Hz, 12.7–226 $kJ \cdot kg^{-1}$) did not result in instrumental texture changes in beef semitendinosus muscle. Up to now, no research has been carried out on determining the effect of PEF processing on lamb meat. Flavor and tenderness are the most appreciated characteristics of lamb meat (Alfonso, 2000). It is also the most important factor that determines acceptability in other species, such as beef (Boleman et al., 1997). Flavor is a very important quality attribute for lamb meat (Crouse, 1983), followed by tenderness. One of the main reasons that some consumers reject lamb meat is its characteristic flavor (Martínez-Cerezo, Sañudo, Panea, & Olleta, 2005). Many studies have investigated the effects of dietary supplementation and cooking methods on the volatile compound profiles of meat (Rivas-Cañedo

et al., 2013; Vasta et al., 2013; Roldán, Antequera, Martín, Mayoral, & Ruiz, 2013). (Z)-2-heptenal, 2,5-dimethylpyrazine, (Z)-2-decenal and (E,E)-2,4-decadienal contribute to roasted meat odor in

grilled lamb meat (Bueno et al., 2011). During storage, lipid oxidation can produce undesirable volatiles such as 2-nonenal, hexanal and 2-octenal, which causing rejection by the consumer (Calkins & Hodgen, 2007; Campo et al., 2006). A recent study (Faridnia et al., 2015) reported that freezing pretreatment with and without PEF greatly affected the volatile profile of beef semitendinosus muscle. Therefore, further studies are required to investigate the effects of chilled and freezing pre-treatments prior to PEF processing of different lamb cuts on the volatile profile and the subsequent sensorial properties of the lamb cuts. Foods do not only undergo a series of physical and chemical reactions during mastication and salivation, but also change in the perception of aroma, taste, flavor and texture. It is well known that the way the food breaks in the mouth affects both the perception of its texture and consumer preferences (Albert, Salvador, Schlich, & Fiszman, 2012). Conventional static sensory assessment is only carried out at a single point evaluation by panelist and it could significantly miss product information. To overcome this drawback, the Temporal Dominance of Sensations (TDS) method has been developed to study the temporal dimensions of flavor perception in themouth to understand the impact of sensory perception over the time of consumption. TDS panelist does not require lengthy training and moreover several attributes can be evaluated simultaneously by TDS (Di Monaco, Su, Masi, & Cavella, 2014). This methodology has been used to study the perception of food such as fish sticks (Albert et al., 2012), low-sodium Mozzarella cheese (Rodrigues, Gonçalves, Pereira, Carneiro, & Pinheiro, 2014), bread (Panouillé, Saint-Eve, Déléris, Le Bleis, & Souchon, 2014), wines (Meillon et al., 2010), and sausage (Devezeaux de Lavergne, Derks, Ketel, deWijk, & Stieger, 2015).

The purpose of this sectiom was to evaluate the effects of chilled and frozen–thawed pre-treatments prior to PEF processing on the flavor and sensory characteristics of cooked lambmeats. In addition, different lamb cuts namely shoulder, loin and ribwere used in this study to understand whether the type of lamb cuts influenced the treatment effects on volatile compounds and sensory profile.

4.4.1. Effect on headspace volatile profile of cooked lamb meat

A total of 24 volatiles that comprised of 1 alcohol, 3 ketones, 7 aldehydes, 3 furans and 10 nitrogen- and sulfur-compounds were found in the headspace of cooked lamb meat using the SPME–GC–MS method. Volatile compounds present in chilled and frozen-thawed lamb meat from different cuts before and after PEF treatment at 0 days and 7 days storage are summarized in Tables 20 and 21 MANOVA results showed that the volatiles of lamb samples was significantly ($p<0.05$) affected by PEF storage, processing and different cuts. All four interactions (storage*processing, storage*cut, processing*storage and storage*processing*cut) were significant (data not are shown).

Table 20 The volatile composition of chilled lamb with and without PEF treatments (mg/100 g dry meat) during 0 or 7 days of storage

No	Volatiles	Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Alcohols																
1	1-Hexanol	0	0.681aA	0.612aB	0.636ayAB	0.643bAB	0.438byC	0.427ayC	0.599yB	0.526byC	0.477byD	0.495byCD	0.684axA	0.645ayB	0.407ayE	0.627B
		7	0.805A	0.675bB	0.828axA	0.675aB	0.713xB	0.495bxC	0.869axA	0.73xB	0.821axA	0.658bxC	0.489byD	0.702xBC	0.694axBC	0.662bC
Ketones																
2	2,3-Octanedione	0	0.951ayA	0.626ayCD	0.629ayCD	0.79ayB	0.667ayC	0.527ayE	0.553ayDE	0.349byB	0.238byD	0.476byA	0.47byA	0.483byA	0.349byB	0.284byC
		7	1.171axB	1.388axA	1.161axB	0.935axC	0.783axD	1.05axBC	1.043xBC	0.859bxBC	0.768bxC	0.923bxAB	0.59bxD	0.573bxD	0.613bxD	1.002xA
3	2-Heptanone	0	0.372byC	0.437BC	0.47byB	0.956xA	0.279bxD	0.374bxC	0.292byD	0.557ayC	0.468yD	0.585ayC	0.856xB	0.827axB	1.017ayA	0.456axD
		7	0.755xA	0.475bC	0.659bxB	0.345bxE	0.508yC	0.624byB	0.43bD	0.665xD	0.753axC	1.099axB	0.513ayE	0.527yE	1.173axA	0.782axC
4	2-Nonanone	0	1.779axB	1.541axC	2.117axA	1.663axBC	1.451aC	1.691axBC	0.812axD	0.309bxB	0.213bxCD	0.138bxE	0.621bxA	0.251bxBC	0.17bxDE	0.228bxCD
		7	0.369ayC	0.818ayB	1.477ayA	0.189ayD	1.233aA	1.364ayA	0.228ayC	0.085byA	0.047byCDE	0.061byBC	0.074byAB	0.04byDE	0.053byCD	0.033byE
Aldehydes																
5	ropanal, 2-meth	0	0.121byF	0.586ayB	0.715ayA	0.323byC	0.208byE	0.275byD	0.238xDE	0.249ayE	0.323byD	0.403byC	0.512aB	0.546aB	0.699aA	0.204yE
		7	0.243bxF	0.769axB	1.127axA	0.642axC	0.409bxDE	0.377bxE	0.484byD	0.531axD	0.622bxC	0.779bxA	0.387bF	0.442aE	0.731aB	0.555axD
6	utanal, 3-methy	0	0.243byF	1.054bA	0.956byB	0.649bxC	0.302byEF	0.354bxE	0.486bxD	1.429ayE	2.269axB	2.035aC	2.602axA	1.966axC	1.78axD	1.003ayF
		7	0.99bxC	1.426B	1.991xA	0.161byE	0.779bxCD	0.805byCD	0.617byD	1.977axB	1.368yC	1.849B	1.414ayC	1.548ayC	1.551ayC	2.24axA
7	utanal, 2-methy	0	0.281byF	1.254aB	1.412ayA	0.948ayC	0.374byE	0.357byEF	0.514ayD	0.46ayBC	0.19byE	0.471byBC	0.359bxD	0.564axA	0.485ayB	0.436bxC
		7	1.535axB	1.554B	2.521axA	0.181xD	0.914axC	0.861axC	0.805axC	0.935bxB	1.274xA	0.843bxB	0.199yD	0.149byD	0.563bxC	0.404byC
8	Hexanal	0	0.163bC	0.431yA	0.199byC	0.184byC	0.131byD	0.174byC	0.245yB	0.544ayB	0.39byC	0.717ayA	0.57aB	0.371ayC	0.411ayC	0.274yD
		7	0.190bD	2.618xA	1.24bxB	0.283bxCD	0.514bxC	0.413bxC	0.463bxC	2.298axB	2.364xB	1.711axC	0.595aF	2.958axA	1.143axE	1.274axD
9	Heptanal	0	0.544A	0.407aB	0.347bxC	0.402bxB	0.268byD	0.36bBC	0.173bE	0.583yB	0.38ayD	0.726ayA	0.51ayC	0.537ayBC	0.565ayBC	0.368ayD
		7	0.542bA	0.393bBC	0.291byD	0.582ayA	0.404axB	0.357bC	0.175bE	2.683axAB	2.985axA	2.237axABC	0.558axD	1.734axBC	1.301axCD	1.138axCD
10	Benzaldehyde	0	1.582ayD	3.058axA	2.622ayB	2.936aA	1.209ayE	1.46ayD	1.874ayC	0.162bC	0.854byA	0.926bxA	0.268bxB	0.16byC	0.172byC	0.109byC
		7	2.31axC	1.993byD	3.246axA	3.206aA	1.882xD	2.218axC	2.91axB	0.143bE	4.407axA	0.507byD	0.121byE	1.988xB	0.251bxE	1.328bxC
11	Nonanal	0	1.014ayAB	1.129aAB	0.959ayBC	0.62ayD	0.756ayCD	1.195aA	1.067aAB	0.304bxB	0.272bBC	0.224bD	0.665axA	0.263byC	0.298byB	0.238bCD
		7	2.36axA	1.242aB	1.069axC	1.237axB	1.138axBC	1.057aC	1.326aB	0.171byE	0.239bCD	0.238bCD	0.265byC	0.367bxB	0.417bxA	0.225bD
Furans																
12	2-Ethylfuran	0	0.049byE	0.085byD	0.157byC	0.262byA	0.254bxA	0.131byC	0.193bB	1.433ayBC	1.286ayC	1.565ayB	1.979axA	1.375aC	1.587ayB	0.818ayD
		7	0.127bxC	0.187bxB	0.217bxB	0.359bxA	0.147byC	0.138bxC	0.208bB	2.215axB	3.056axA	2.294axB	1.095ayE	1.168aE	1.817axC	1.439axD
13	2-Vinylfuran	0	0.392byBC	0.372byBC	4.082aA	0.467byB	0.538byB	0.226byC	0.532byB	0.92aB	0.638ayD	0.629byD	1.893axA	0.696ayCD	0.816ayBC	0.678ayCD
		7	2.289axC	2.854axB	4.103aA	2.537axBC	1.086axD	0.494bxE	0.863axDE	1.012bBC	1.105bxA	0.829bxE	0.89byDE	1.075axAB	1.062axAB	0.94axCD
14	2-Pentylfuran	0	0.51ayD	0.905axAB	0.845aB	0.925axA	0.463ayD	0.609ayC	0.469ayD	0.239bC	0.347bxB	0.501bxA	0.218bxCD	0.209byD	0.13byE	0.197byD
		7	0.946axA	0.651ayD	0.86aB	0.341ayE	0.738axC	0.726axC	0.712axCD	0.286bC	0.164byE	0.209byD	0.133byE	0.48bxA	0.202bxD	0.343bxB

No	Volatiles	Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Nitrogen and sulfur compounds																
15	Pyridine	0	0.023byD	0.001byD	0.107byC	0.264bxB	0.383byA	0.135byC	0.269byB	2.764ayB	3.19ayA	2.455ayC	3.428aA	3.225ayA	3.202ayA	3.351ayA
		7	0.382bxC	0.009bxE	0.141bxD	0.027byE	0.402bxC	1.449bxB	1.544bxA	4.185axBC	4.472axA	4.1axC	3.821aD	4.386axAB	4.094axC	4.052axCD
16	Pyrrole	0	0.593ayA	0.309ayC	0.257ayD	0.252byD	0.241byD	0.248ayD	0.365ayB	0.349bxC	0.155bxDE	0.217axD	0.775axA	0.433axB	0.155byDE	0.147byE
		7	3.664axCD	8.259axA	3.388axD	7.016axB	3.733axC	2.612axE	3.314axD	0.04byA	0.025byBC	0.039byA	0.029byABC	0.041byA	0.036bxAB	0.022bxC
17	Pyrazine, methyl	0	0.022byE	0.237byBC	0.167byD	0.339byA	0.273byB	0.227byC	0.13byD	0.796ayC	1.082ayB	0.895ayC	0.623ayD	1.39ayA	0.323ayE	0.37ayE
		7	1.054bxF	2.254bxC	2.661bxB	1.107bxEF	3.141bxA	1.371xD	1.286bxDE	1.691axC	2.637axB	4.295axA	1.41axC	4.572axA	1.545xC	1.542axC
18	Pyrazine, 2-ethyl-3-m	0	0.656byB	0.101byE	0.653byB	0.546yC	0.202byD	0.92byA	0.496byC	2.471ayB	3.731ayA	2.353ayB	0.557yE	1.004ayD	1.375ayC	0.614ayE
		7	8.326bxC	7.212axD	9.197bxB	9.736bxA	1.328bxE	1.546bxE	8.49bxC	11.591axC	7.177axD	12.735axB	13.67axA	6.398axE	6.601axDE	11.971axC
19	Pyrazine, 3-ethyl-2,5-di	0	2.749byB	0.982byD	2.837byB	1.95byC	1.062byD	3.334byA	1.883yC	9.568ayB	16.503aA	8.643ayB	5.827ayC	4.993ayCD	4.484ayD	1.778yE
		7	9.89bxB	10.195bxB	17.53bxA	2.586bxE	5.395bxD	5.617bxD	8.504bxC	22.001axB	16.752aD	24.907axA	24.319axA	19.625axC	19.877axC	14.712axE
20	Pyrazine, 3,5-diethyl-2-r	0	2.288byB	1.298bD	1.984byC	3.028bA	0.548byF	0.369byG	1.001byE	9.247ayC	1.998ayE	8.57ayC	6.397aD	22.388axA	17.145aB	6.337axD
		7	2.776bxB	1.322bD	3.54bxA	3.066bB	1.797axC	1.821bxC	2.005bxC	30.345axA	27.654axA	24.561axB	6.931aD	1.873ayE	17.503aC	3.947ayE
21	Thiophene	0	1.794ayBC	1.645ayCD	2.163ayA	1.895ayB	1.564yDE	1.404yE	2.109ayA	0.81byD	0.463byF	1.046byC	0.645byE	1.647xA	1.288yB	0.718byDE
		7	2.86xA	2.61xB	2.996axA	2.994axA	2.293axC	2.22axC	2.618axB	2.674xB	2.842xA	2.696bxB	0.97bxD	0.762byE	1.825bxC	1.001bxD
22	Dimethyl disulfid	0	0.56bA	0.512byBCD	0.498byCD	0.556byAB	0.544byAB	0.518byABC	0.471byD	2.177ayB	1.597ayD	1.897ayC	2.547axA	1.767ayC	1.795ayC	1.859ayC
		7	0.649bAB	0.611bxB	0.637bxAB	0.686bxAB	0.691bxAB	0.689bxA	0.705bxA	3.25axA	3.179axA	2.763axC	2.268ayE	2.995axB	2.608axD	2.538axD
23	Furanmethaneth	0	5.013ayD	14.492aB	17.585ayA	13.074aC	1.785ayE	1.311ayE	13.016ayC	0.483byCD	0.605bB	0.441byE	0.65bxA	0.457byDE	0.503byC	0.475byCDE
		7	15.329axB	14.704aB	20.533axA	13.516aC	12.208axD	13.249axC	9.642axE	0.568bxB	0.663bA	0.559bxB	0.572byB	0.677bxA	0.591bxB	0.562bxB
24	Dimethyl trisulfid	0	2.346byD	2.601aC	2.303bD	2.606yC	3.212bxA	2.811bxB	2.028bxE	3.737ayC	0.709byE	3.212ayCD	2.616D	12.216ayA	10.174ayB	2.575ayD
		7	2.716bxA	2.167bB	2.189bB	2.878xA	1.826byC	2.143byB	1.828byC	16.358axB	19.443axA	15.505axB	2.821D	13.022axC	12.228axC	3.137axD

[a,b] means with different letters in row show significant effect of processing in each cut; [x,y] means with different letters in column show significant effect of storage in each cut in same processing; [A,B,C,D,E,F] means with different letters in row show significant effect of cut in each processing using Fisher's least significant difference ($p < 0.05$).

Table 21 The volatile composition of frozen-thawed lamb with and without PEF treatments (mg/100 g dry meat) during 0 or 7 days of storage

No	Volatiles	Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Alcohols																
1	1-Hexanol	0	0.925yA	0.714ayBC	0.948ayA	0.826yAB	0.61byC	0.6yC	0.83ayAB	1453A	0.509byC	0.702byBC	0.976yB	0.657ayC	0.663C	0.529byC
		7	1.249xB	1.914axA	1.443xB	1.225bxB	1.364xB	1.366axB	1.42xB	1.386AB	0.755bxC	1.508xA	1.393axAB	1.309xB	0.707bC	1.417xAB
Ketones																
2	2,3-Octanedione	0	2.37byB	0.844axC	0.952byC	3.022ayA	3.182ayA	0.939ayC	0.237byD	5.072aA	0.674byE	1.562ayBC	1.815byB	1.209byCD	0.951ayDE	0.801ayDE
		7	3.464bxBC	0.263byE	3.153bxC	4.165bxAB	5.022xA	2.059bxD	5.169axA	4.704aC	2.959axE	6.177axB	10.805axA	4.71xC	3.484axDE	4.479bxCD
3	2-Heptanone	0	0.165byD	0.22yD	1.072ayA	0.225byD	0.835aB	0.424yC	0.464ayC	1.708ayA	0.267yC	0.576byB	0.569ayB	0.486byBC	0.413yBC	0.299byC
		7	1.031bxBC	1.17xB	1.538bxA	0.499bxE	0.773bD	0.541bxE	0.971bxC	3.588axBC	1.072xE	5.027axA	3.971axAB	2.481axCD	1.548axDE	3.198axBC
4	2-Nonanone	0	1.257axC	0.706ayD	2.838aA	0.519ayD	1.952axB	1.144aC	0.623ayD	0.061b	0.068bx	0.066by	0.082by	0.066by	0.082by	0.073b
		7	0.955ayDE	3.614axA	2.484aB	0.729axE	1.359ayC	1.127aCD	1.004axDE	0.188bAB	0.047byD	0.184bxBC	0.258bxAB	0.117bxBC	0.198bxAB	0.098bC
Aldehydes																
5	ropanal, 2-meth	0	2.542axA	0.314ayC	0.814ayB	0.52yBC	0.327yC	0.263yC	0.221yC	1.091byA	0.23byC	0.457byB	0.441yB	0.443yB	0.318yBC	0.209yC
		7	3.031axB	4.478axA	2.959xB	5.194xA	1.885xC	1.902axC	2.806axB	1.249byA	0.818bxC	4.387xA	4.094xA	2.594xB	1.575bxBC	0.727bxBC
6	utanal, 3-methy	0	0.585byD	0.675yCD	1.005byA	0.31byE	0.836byB	0.746BC	0.763byBC	2.005ayB	0.76yD	2.097ayB	1.182ayC	1.207ayC	0.911yCD	5.442ayA
		7	6.501xB	9.136axA	6.744xB	6.89xB	4.021xC	4.344aC	9.511axA	5.062xABC	1.931bxD	6.796xAB	7.028xA	5.333xABC	3.637bxCD	4.567bxBC
7	utanal, 2-methy	0	0.448byDE	0.816ayC	2.135ayB	0.191ayE	0.759ayCD	0.722aCD	6.737ayA	0.768ayA	0.114byD	0.738byA	0.292ayBC	0.228byCD	0.384byB	0.185byCD
		7	8.075axCD	10.819axB	9.018axC	6.725axDE	5.02axF	5.346aEF	13.477axA	1.787bxAB	0.769bxC	2.073bxA	1.379bxB	0.605bxC	0.668bxC	1.452bxB
8	Hexanal	0	0.132byD	0.168byD	0.441byA	0.149byD	0.303bC	0.186ybD	0.374yB	2.422ayA	0.556ayC	1.753ayB	0.661ayC	0.504ayC	0.679ayC	0.535yC
		7	0.676bxA	0.346bxC	0.576bxB	0.293bxC	0.374bC	0.33xbC	0.743bxA	5.256axA	1.969axB	5.574axA	4.524axA	1.598axB	1.711axB	4.439axA
9	Heptanal	0	0.201byC	0.187bC	0.268bBC	0.314byAB	0.388xA	0.269bBC	0.184byC	2.433ayA	0.517ayBC	2.254ayA	0.611ayBC	0.527yBC	0.864ayB	0.513ayC
		7	0.336bxAB	0.271bBC	0.336bAB	0.205bxC	0.279byBC	0.117bD	0.404bxA	5.289axAB	1.813axC	6.169axA	4.213axB	1.616axC	1.895axC	4.459axB
10	Benzaldehyde	0	0.968yEF	1.196yDE	3.044ayB	0.841ayF	1.538ayC	1.456ayCD	4.131ayA	1.282A	1.31yA	0.438byBC	0.528byB	0.36byCD	0.226byD	0.314byCD
		7	5.024axB	5.844axA	4.327axBC	4.336xbBC	3.312axD	3.997axCD	6.159axA	1.135bB	1.925bxB	1.117bxB	10.116axA	0.852bxB	0.544bxB	1.388bxB
11	Nonanal	0	0.77yBC	0.692ayC	0.699ayC	0.922ayB	1.226aA	0.922aB	0.728ayBC	0.691A	0.082byDE	0.153byD	0.591bB	0.41bC	0.084byDE	0.045byE
		7	3.279axA	2.234axB	1.96axBC	1.734axC	1.33aD	1.324aD	3.631axA	0.719bB	0.262bxD	0.627bxB	1.971aA	0.407bC	0.17bxD	0.46bxC
Furans																
12	2-Ethylfuran	0	3.162xA	0.444bxB	0.151byBC	0.31byBC	0.231byBC	0.286byC	0.321byC	4.051A	0.835ayB	1.836ayB	0.833ayC	1.203ayCD	1.734ayCD	0.661ayD
		7	2.383byA	0.124byB	0.553bxB	0.12bxB	0.479bxC	0.147bxC	0.52bxC	4.419aA	1.82axB	4.107axA	4.048axA	2.428axB	2.587axB	4.412axA
13	2-Vinylfuran	0	0.526bxD	3.993axB	0.274byDE	2.162axC	0.02byE	0.697yD	4.504ayA	1.483aA	0.51byEF	0.857ayD	1.3bB	0.981ayC	0.568yE	0.443byF
		7	0.226byF	1.043yE	5.778axA	0.917byE	2.457axD	3.037axC	5.238axB	1.952aB	0.951xBC	2.05bxB	4.044aA	1.262bxBC	0.7bxC	1.473bxBC
14	2-Pentylfuran	0	0.241ayD	0.282ayD	1.133ayA	0.277byD	0.914aB	0.531ayC	0.154byD	0.08bE	0.171bxD	0.522bxA	0.427ayBC	0.442bB	0.207bD	0.365ayC
		7	1.761axAB	1.609axB	2.029axA	0.714axC	0.991aC	0.848axC	1.646axB	0.088bD	0.084byD	0.235byC	0.197bxC	0.404bA	0.206bBC	0.29bxD

No	Volatiles	Storage	Control							PEF						
			Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
Nitrogen and sulfur compounds																
15	Pyridine	0	0.032bAB	0.037bA	0.028byBC	0.032byAB	0.011byD	0.025bC	0.032bAB	6.116ayA	3.482ayDE	4.47ayC	5.202aB	3.724ayD	3.86aCD	2.966ayE
		7	0.031bC	0.03bC	0.046bxB	0.082bxA	0.075bxA	0.02bD	0.035bC	7.21axAB	3.852axD	8.255axAB	9.105aA	4.265axCD	3.512aD	6.087axBC
16	Pyrrole	0	0.725axA	0.232ayD	0.409ayB	0.418ayB	0.374ayBC	0.306ayCD	0.429ayB	0.032byB	0.021byE	0.024byCDE	0.053byA	0.025byCD	0.027byC	0.023byDE
		7	0.596ayCD	0.92axA	0.676axC	0.517axD	0.679axC	0.501axD	0.807axB	0.049bxB	0.038bxC	0.033bxDE	0.063bxA	0.033bxD	0.036bxCD	0.03bxE
17	Pyrazine, methyl	0	0.171yD	1.239ayB	1.245ayB	0.142byD	0.685ayC	1.197ayB	4.538ayA	0.367yA	0.262byD	0.315bBC	0.346aAB	0.321byABC	0.286byCD	0.169byE
		7	12.076axA	8.368axB	7.029axBC	3.949axE	5.139axDE	6.653axCD	12.099axA	0.68bxAB	0.595bxAB	0.29bB	0.989bA	0.47bxB	0.593bxAB	0.731bxAB
18	Pyrazine, 2-ethyl-3-m	0	2.541ayD	4.614ayBC	4.396ayC	1.088ayE	3.253ayD	5.298aB	9.425ayA	0.969byB	0.52byBC	2.138byA	0.19byD	0.993bB	2.09byA	0.419byCD
		7	22.308axA	20.521axAB	17.037axC	7.923axD	16.642axC	4.399aE	19.442axB	2.487bxA	1.03bxB	3.135bxA	2.649bxA	0.711bB	1.066bxB	2.294bxA
19	Pyrazine, 3-ethyl-2,5-di	0	8.165ayCD	11.378ayB	14.495ayA	2.006yE	6.804ayD	9.796ayBC	14.277ayA	2.247byC	1.44byC	6.72byA	1.877C	3.506bB	7.166bA	1.539byC
		7	32.412axD	36.442axC	40.596axB	8.933xE	35.015axCD	7.524aE	45.761axA	9.317bxA	2.321bxB	9.277bxA	8.155A	2.523bB	3.901bxB	6.861bxA
20	Pyrazine, 3,5-diethyl-2-r	0	2.466byB	1.179byCD	1.36byC	3.187byA	0.997byD	1.287byCD	2.354byB	10.374A	3.234aB	11.49aA	5.014ayB	10.573axA	9.35ayA	4.881ayB
		7	3.487xCD	6.507axA	4.388bxBC	4.154bxBC	3.082xD	3.91bxBCD	4.443bxB	8.326aCD	2.811bE	11.799aAB	9.778axBC	2.98yE	6.594axD	13.446axA
21	Thiophene	0	3.198ayAB	3.081ayAB	2.442ayC	3.559aA	2.461ayC	2.72yBC	2.466ayB	2.145bB	1.019byC	1.804bB	1.149bC	1.113bC	2.709yA	0.933byC
		7	5.149axAB	4.899axBC	5.77axA	4.276B	5.329axAB	4.772axBC	4.279axC	2.107bAB	1.238bxC	2.227bAB	2.696A	1.255bC	1.574bxBC	2.041bxABC
22	Dimethyl disulfid	0	0.726bB	0.596bC	0.433byD	0.729byB	0.803byA	0.711byB	0.583byC	4.65ayA	2.412ayE	3.338ayC	3.985ayB	2.963ayCD	2.528ayE	2.647ayDE
		7	0.7bC	0.674bC	0.698bxC	0.822bxAB	0.876bxA	0.78bxABC	0.722bxBC	5.775axB	3.814axC	6.12axAB	6.956axA	3.943axC	3.584axC	6.053axB
23	Furanmethaneth	0	2.214ayD	9.435ayA	10.463ayA	2.243ayD	7.419ayB	4.586aC	2.492ayD	0.824bA	0.72byB	0.614byC	0.838bA	0.717bB	0.692byB	0.639byC
		7	42.545axAB	36.899axC	39.409axBC	7.972axD	36.192axC	4.146aE	44.416axA	0.861bBC	0.971bxAB	0.804bxBC	1.106bA	0.798bC	0.825bxBC	0.901bxBC
24	Dimethyl trisulfid	0	3.553bAB	2.428bBC	2.329byBC	4.528aA	2.06byC	2.295bBC	2.943aBC	11.757aAB	2.768ayC	7.885aB	2.069byC	9.58aAB	12.031ayA	3.217ayC
		7	2.437bD	2.6D	3.048bxBCD	4.321bA	3.257bxBC	2.847bCD	3.511bB	9.245aB	3.533xC	10.398aB	11.011axAB	4.34aC	8.315axB	14.353axA

[a,b] means with different letters in row show significant effect of processing in each cut; [x,y] means with different letters in column show significant effect of storage in each cut in same processing; [A,B,C,D,E,F] means with different letters in row show significant effect of cut in each processing using Fisher's least significant difference ($p < 0.05$).

Effect of Storage

During storage, hexanal (8) levels increased significantly ($p < 0.05$) in samples of all chilled and frozen-thawed samples (except frozen-thawed shank cut). Hexanal is mainly generated during the oxidation of linoleic acid (Purriños, Franco, Carballo, & Lorenzo, 2012). Its concentration is an indicator of lipid oxidation and contributes to the formation of flavor in cooked beef meat (Yang, Lee, Moon, Paik, & Ahn, 2011). The Strecker degradation of amino acids is a key reaction in the generation of potent aroma compounds during Maillard-type processes (Mottram, 1998). No significant increase ($p < 0.05$) in 3-methyl butanal (6) was observed in chilled loin samples and frozen-thawed shoulder samples stored for 7 days. This compound has been reported in cooked beef (Machiels & Istasse, 2003) and goat (Madruga, Stephen Elmore, Dodson, & Mottram, 2009). It has been described as malty and fatty (Burdock & Fenaroli, 2010), and is an important volatile compound in dry-cured ham products. In addition, Ruiz, Ventanas, Cava, Andrés, & García (1999) reported that 3-methylbutanal was found in high concentrations in longer aged hams. Within 7 days period, chilled meat showed no significant differences of benzaldehyde (10) content in rib samples. However, with freezing pre-treatment, benzaldehyde was significantly ($p < 0.05$) higher in 7 days stored rib samples. This may be attributed to increased protein degradation in meat with freezing condition and longer storage. Sulfur containing compounds, furans and thiophenes and related disulfides are known to possess strong meat-like aromas and exceptionally low odor threshold values (Huang & Ho, 2012). Mottram (1998) reported that sulfur volatile compounds are derived from sulfur containing amino acid degradation. Koutsidis et al (2008) concluded that the concentration of cysteine increased threefold during storage, which may also be responsible for increased flavor intensity in aged meat. The potent sulfur-containing compounds can be formed from the reaction between cysteine and ribose when meat is cooked. Dimethyl disulfide (24) increased significantly ($p<0.05$) in all chilled (except knuckle) and frozen-thawed

(except knuckle and loin) samples from 0 to 7 days storage. Huang & Ho (2012) detected sulfur volatiles, such as dimethyl sulfide, dimethyl disulfide, and dimethyl trisulfide in pork and beef. Dimethyl trisulfide comes from the condensation of methanethiol and methional or 3-(methylthio)-propanal formed by the oxidative catabolismofmethionine via Strecker degradation (López Del Castillo-Lozano, Delile, Spinnler, Bonnarme, & Landaud, 2007). Stetzer, Tucker, McKeith, & Brewer (2008) found that beef from various muscles including *gluteus medius, rectus femoris, vastus lateralis, vatsus medialis, teres major, complexus, serratus ventralis, psoas major and longissimus dorsi* of heifer carcasses that were chill aged for 7 or 14 days produced flavor-active volatiles that included 2,3-octanedione and 2-pentyl-furan. These volatiles are often associated with lipid oxidation and are affected by enhancement and aging in the various muscles. In this study, 2,3-octanedione (2) increased significantly ($p<0.05$) in all chilled and frozen-thawed (except knuckle) samples. Results from our study showed chilled samples (except rump cut) had significantly high level ($p<0.05$) of 2-pentylfuran after 7 days storage. Siegmund & Pfannhauser (1999) reported that the relative concentrations of the lipid oxidation products 1-octen-3-ol and 2- pentylfuran increased in cooked chill stored chicken meat as storage time increased. While, frozen-thawed shank sample had significantly high level ($p < 0.05$) of 2-pentylfuran only after 7 days storage.

Effect of PEF

Regarding of PEF effect, hexanal (8), heptanal (9) had been drastically greater ($p< 0.05$) in PEF treated chilled (rump, rib, shank and shoulder) and frozen-thawed (knuckle, loin, rump, rib and shoulder) cuts. Heptanal was generated from the oxidized oleic acid in beef fat (Machiels, Istasse, & Van Ruth, 2004). 3-methyl butanal (6) and 2-methyl butanal (7) were significantly higher ($p< 0.05$) in PEF treated chilled (knuckle, shank and shoulder) and frozen-thawed (knuckle and rib) cuts. 3-Methylbutanal and 2-methyl butanal are Strecker degradation product (Mottram, 1998), which are formed by leucine. 3-methyl butanal was also contributed to the roasted

beef flavor (Machiels et al., 2004). Dimethyl disulfide (22) was significantly higher ($p<0.05$) in PEF treated chilled (except loin and rib) and frozen-thawed (except rib) cuts. Mottram (1998) reported that the degradation of sulfur-containing amino acids, especially cysteine, resulting in generation of sulphur containing volatile compounds. However, cysteine was not detected due to the limitation of the EZ-faast kit. In addition, the 2,3-octanedione (2) was significantly higher ($p<0.05$) in PEF treated frozen-thawed (except loin, rib and shank) cuts. Stetzer et al (2008) reported that 2,3-octanedione had a oxidized fat and warmed over flavour which is derived from lipid oxidation. This result can be explained by higher lipid oxidation in frozen-thawed cuts.

Effect of Cut

Aldehydes, in general, are not stable and can easily react with other compounds to produce compounds, which result in different flavors (Mottram, 1998). There was a significantly ($p<0.05$) higher level of hexanal present in chilled loin and frozen-thawed rump cut. Hexanal, together with other volatile aldehydes such as heptanal, octanal and nonanal, are important in cooked beef flavor, and may impart a pleasant fruity flavor at low concentration (Machiels et al., 2004). Heptanal had significant high level of chilled knuckle cut and frozen-thawed shank cut. Low concentration of 2-methyl propanol and 3-methyl butanal were found in chilled rib and frozen-thawed shoulder cut. Several Strecker aldehydes that are well-known cooked beef components, such as 2-methyl propanol (5), 3-methyl butanal (6), and 2- methyl butanal (7) may be derived from valine, leucine and isoleucine, respectively (Huang & Ho, 2012).The alcohol, 1-hexanol (1), derived from hexanal reduction, was present in relatively low concentrations. In this study, 1-hexanol was present in the all shoulder cut sample at significantly low levels ($p<0.05$) compared to others cut. This aroma impact compound has been associated with smoke or smoked food products (Varlet, Knockaert, Prost, & Serot, 2006).In addition, benzaldehyde (10) was significantly ($p<0.05$) highest in the chilled rib cut than others,

whereas significantly highest benzaldehyde was found in the frozen-thawed knuckle.

Ketones are generated in reasonably large amounts during cooking of beef due to lipolysis (Rochat & Chaintreau, 2005). 2-heptanone (3) were present in significantly higher levels ($p<0.05$) in both chilled rib cut and frozen-thawed rump cut. On the other hand, 2,3-octanedione (2) were present in significantly higher levels ($p<0.05$) in chilled knuckle cut and frozen-thawed shank cut. 2,3-octanedione can be derived from the heating and breaking down of linoleic acid (Calkins & Hodgen, 2007). From fatty acids result above, Chilled knuckle cut and frozen-thawed shank cut had significant high level of linoleic acid.

2-Pentylfuran (14), with beany and grassy type sensory properties, has a low threshold value of 6×10^{-3}mg/kg (Maarse & Visscher, 1989). Chilled and frozen-thawed knuckle and topside cut samples had a significantly low concentration of 2- pentylfuran compared to rump cuts.

Volatile compounds that include nitrogen, sulfur and nonheterocyclic compounds are formed due to the Maillard reaction. Large amounts of 2-furanmethanethiol (23) were present in the meat sample, with the chilled and frozen-thawed loin and rump cuts having significantly higher levels ($p < 0.05$) of this compound compared to shoulder and shank cuts. 2-furanmethanethiol (furfuryl mercaptan) was reported as being formed from the breakdown of ribose via the Maillard reaction (Mottram & Nobrega, 2002). It has been shown to be an important contributor to cooked goat and chicken aroma, as it possesses roast, nutty, burnt and meaty notes (Aliani & Farmer, 2005; Madruga et al., 2009; Mottram, 1998). Pyrazines are generally associated with nonenzymatic browning, which generally possesses roasted, nut-like notes (Reineccius, 2005). Regarding of chilled meat, 2-ethyl-3-methyl-pyrazine (18) and 3,5-diethyl-2-methyl-pyrazine (20) in the topside cut was significantly high ($p < 0.05$) compared to shoulder and shank cut sample. The frozen-thawed topside sample had a significantly higher level ($p < 0.05$) of methyl-pyrazine (17), 2-ethyl-3-methyl-pyrazine (18) and 3,5-

diethyl-2-methyl-pyrazine (20) than other cuts (except knuckle and rib). This may indicate more nonenzymatic browning happened in the topside cut.

A multivariate study of volatiles from different cuts of cooked lamb before and after PEF treatment after 0 and 7 days of storage

For the chilled and frozen-thawed meat data, separate Canonical Variate Analyses (CVA) was carried out on the volatiles of non-PEF and PEF treated meat cut at 0 and 7 days storage (Fig. 27 and 28). Sample discrimination was explained by the first two canonical variates, which were 68.09 % for chilled meat data, and 73.5% for frozen-thawed meat data. MANOVAs were significant for both chilled meat ($F_{(648,271)}$ =845.446; $p < 0.0001$) and frozen-thawed meat ($F_{(648,271)}$ =239.039; $p < 0.0001$) data.

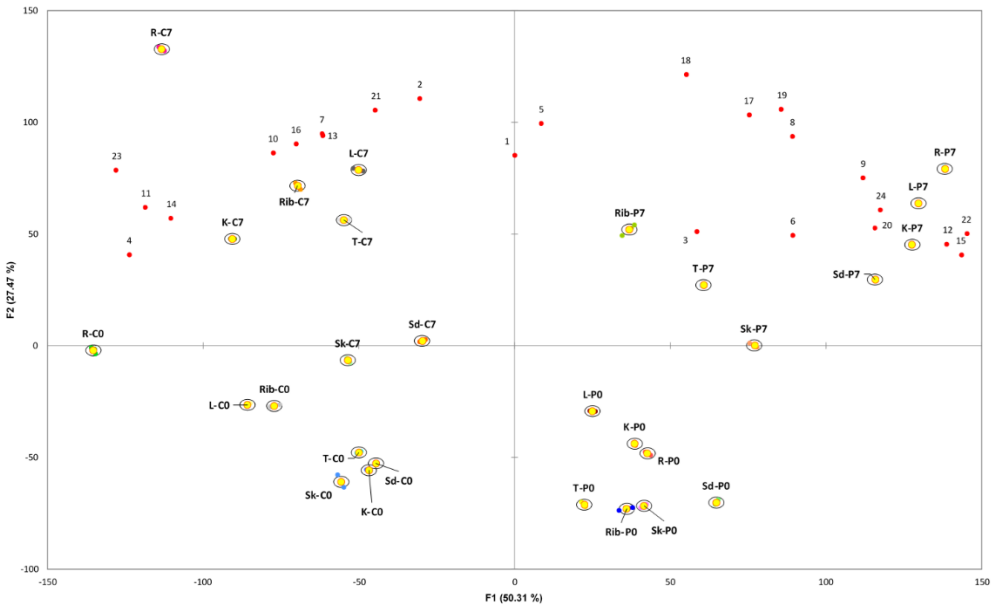

Figure 27 Canonical Variate Analysis Biplot of volatiles for non-PEF and PEF treated chilled lamb meat with different cuts. The variables are numbered the same as in Table 20 Hotteling-Lawley MANOVA test showed significant product differences (F (648,271) =845.446; $p < 0.0001$) based on free amino acids. Each point represents data from a single observer. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; S=Shank; T=Topside; C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage.

CVA plot of volatiles for chilled meat shown in Fig 27 described 50.31% and 27.47% of the total variation of factor 1 (F1) and factor 2 (F2), respectively. For chilled meat, it is clear that all cuts with PEF treatment at 0 and 7 days storage had high positive scores and were separated from control samples

along F1. It is clear that the 0 and 7 days storage samples (except shank and shoulder) were further separated along F2,with the former having negative scores and the latter positive scores. Non-PEF treated samples at 7 days storage (C7) corresponded to high negative loadings (F1) of benzaldehyde (10). This volatile compound was found to be significantly higher concentration ($p< 0.05$) as shown in Table 20. Similarly Faridnia et al. (2015) reported that benzaldehyde decreased after PEF in the volatiles of chilled beef semitendinosus muscle, but not significantly ($p < 0.05$). It was also found that a total of three aldehydes, including 3-methyl butanal (6), hexanal (8), and heptanal (9), were associated with the PEF samples that had high positive scores along F1 and were separated from the non-PEF treated samples (Fig 27). Hexanal (8) concentration represented the status of lipid oxidation and the formation of flavor in cooked beef meat (Yang et al., 2011). Heptanal, arise mainly from the oxidation of oleic acid, which is the main fatty acid in beef fat (Machiels et al., 2004). The increasing level may be due to lipid oxidation during the PEF processing. Only significantly enhanced TBARS values were obtained, when PEF treatment was applied to frozen-thawed beef semitendinosus muscle according to Faridnia et al. (2015). The chilled non-PEF samples corresponded to high negative loadings of 2-pentylfuran (14). The n-3 derived compounds 2-ethylfuran (12) was present in PEF treated samples that corresponded to high positive loadings along F1. CVA also showed that volatile compounds like heptanal (9), 3,5-diethyl-2-methyl-pyrazine (22), and dimethyl trisulfide (24) were associated with the PEF treated loin, knuckle and rump cut stored for 7 days (L-P7, K-P7 and R-P7) that had high positive scores along F2. However in-PEF treated R cut stored for 7 days (R-C7) were associated with 2,3-octanedione (2) and pyrrole (16) that had negative scores along F1.

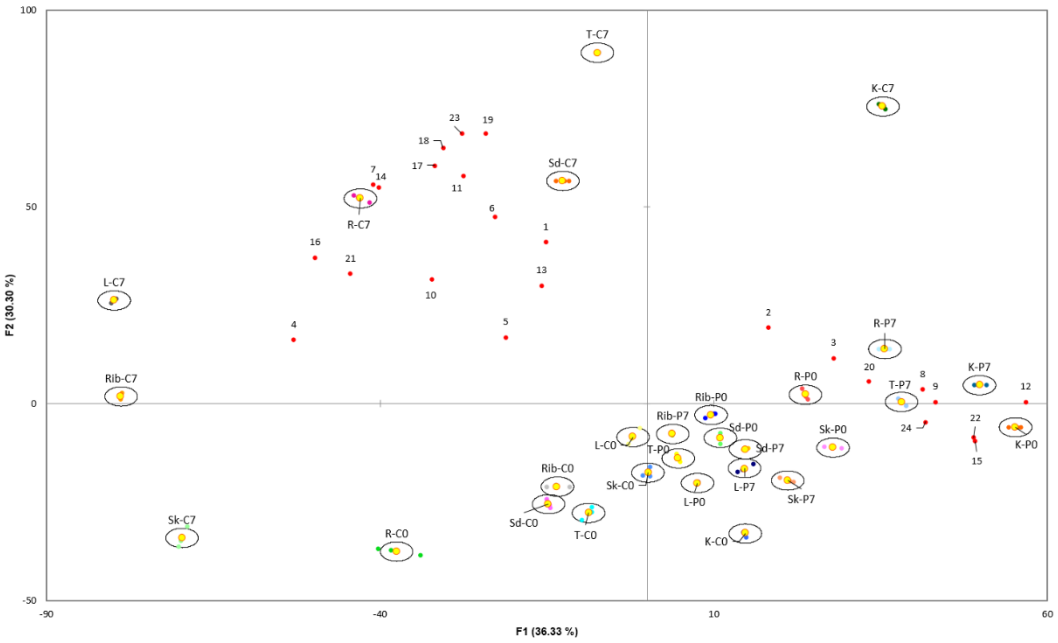

Figure 28 Canonical Variate Analysis Biplot of volatiles for non-PEF and PEF treated frozen-thawed lamb meat with different cuts. The variables are numbered the same as in Table 21 Hotteling-Lawley MANOVA test showed significant product differences ($F_{(648,271)} = 239.039$; $p < 0.0001$) based on free amino acids. Each point represents data from a single observer. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; S=Shank; T=Topside; C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage.

CVA plot of volatiles for frozen-thawed meat shown in Fig 28 described 36.33% and 30.30% of the total variation of factor 1 (F1) and factor 2 (F2), respectively. For frozen-thawed samples, not-PEF treated cuts, except for knuckle (K-C0 and K-C7) and PEF treated cuts were clearly separated along F1, non-PEF treated samples had negative scores and PEF treated samples had positive scores. It also found that non-PEF treated samples stored at 7 days, except rib (Rib-C7) and shank (Sk-C7), had high positive scores and separated from other samples. It was found that a total of five volatile compounds were associated with the knuckle cut except non-PEF treated 0 storage (C0) that had high positive ranking along F1 (Fig 28).These volatile compounds included 2,3-octanedione (2), 2-heptanone (3), hexanal (8), heptanal (9), and 2-ethylfuran (12) that had positive loadings along F1. Nitrogen and sulfur compounds, such as pyrrole (16), pyrazine, methyl- (17), pyrazine, methyl- (18), and pyrazine, 3-ethyl-2,5-dimethyl- (19), and 2-

Furanmethanethiol (23), were associated with the non-PEF treated topside shoulder and rump at 7 days storage (T-C7, Sd-C7 and R-C7) that had high positive scores along F2.These results indicated that different storage, cut, non-PEF and PEF treatment affected the volatile profile of frozen-thawed meat, but PEF treatment had less significant effect the volatiles of lamb meat cuts than aging compared to chilled samples. This may be due to the higher electrical conductivities by freezing and thawing, which cause inefficient field strength on meat and less proteolysis reaction.

4.4.2. Sensory evaluation

Initial tenderness

The initial tenderness of PEF and non-PEF treated chilled and frozen-thawed meats was evaluated on the first bite by panelists prior to carrying out TDS (Table 22). Interestingly, sensory tenderness was not found to be significantly different between all cooked lamb samples in terms of cuts, storage and PEF processing (electric field strength of 1– 1.4 $kV \cdot cm^{-1}$), and their interactions. Similarly, O'Dowd et al. (2013) reported that PEF treatments with an electric field strength 1.90 kV. cm−1 did not affect the instrumental texture values of beef *semitendinosus*. Morton, Bickerstaffe, Kent, Dransfield, & Keeley (1999) examined the shear strength, pH, temperature, μ-calpain, m-calpain and calpastatin levels in *longissimus lumborum et thoracic* (LD) from six lamb and six beef carcasses over a two-week post-slaughter period. All carcasses were subjected to high voltage electrical stimulation. At 12 h post-slaughter, lamb LD was tougher than beef LD. However the subsequent rate of tenderisation was 50% faster than the beef LD. Consequently at 48 h post-mortem, the lamb LD was more tender than beef LD. In this study, it could be that lamb meat was already tender prior to PEF treatment and hence did not significantly increased tenderness.

Table 22 Initial tenderness in chilled and frozen-thawed control and PEF treated lamb meat at 0 and 7 days storage for each cut

Storage	Control							PEF						
	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside	Knuckle	Loin	Rump	Rib	Shank	Shoulder	Topside
0	6.86	6.13	6.84	6.59	6.54	6.55	6.59	6.96	6.14	6.78	6.13	6.93	7.51	6.86
7	7.26	6.23	6.58	6.02	6.99	6.02	6.73	6.93	6.72	6.97	6.23	7.34	6.13	7.13
0	6.63	6.49	5.91	6.17	5.94	5.92	6.44	6.72	6.23	6.31	6.78	6.81	6.16	5.67
7	6.64	6.69	6	6.94	6.08	6.25	5.86	6.34	5.83	6.46	6.37	6.65	5.35	6

Panel dominance curves

Figs. 29 and 30 show smoothed TDS curves using the Spline equation for all samples. Two lines were added to represent the chance and significant levels. The chance level represents the dominance rate that an attribute could attain by chance (1/number of attributes), while the significance level expresses the smallest value of the proportion that is significantly ($p < 0.05$) higher than the chance level. When the TDS curves rise from between the chance and the significance levels to above the latter, they are consistent at panel level (Albert et al., 2012). In this study, with the use of trained panelist, the chance level was found to be 0.20, corresponding to a dominance rate of 20%. Therefore, meat attributes below 20% were not considered as dominant. Similarly other TDS studies using trained panels have reported chance levels of 20% for flavored gels (Labbe et al., 2009) and dairy products (Pineau et al., 2009). The significance level was calculated considering the chance level and the 90 evaluations performed (10 panelists that participated in triplicate trials). A significance level of 0.37 was obtained, corresponding to a dominance rate of 37%. TDS panel dominance curves afford identification of both dominance rate and time of evaluated attributes. Meaty, juicy, browned livery and oxidized were dominant attributes in our study. Beef flavor meat lexicons that described attributes found in red meats have been reported in the literature (Gasperi et al., 2005; Maughan et al., 2012; St. Angelo et al., 1991). Relating the lexicon to consumer acceptance allows for classification of these attributes as positive or negative attributes for a specific consumer market. Terms associated with "positive" attributes are: meaty, roast beef, juicy, browned, fatty, and

salty. Terms associated with "negative" attributes include: oxidized, bitter, barny, gamey, grassy, livery, metallic, and astringent (Maughan et al., 2012). Monsón et al. (2005) and Spanier, Flores, McMillin, and Bidner (1997) observed in beef that desirable beef flavors such as beefy, meaty, browned/caramelized, and sweet gradually started to decline after 4 – 10 days storage, whereas bitter, sour, painty, and cardboard slowly became more pronounced.

TDS curves distinguished the effect of aging and different cuts in terms of dominant sensory attributes of the samples. Fig. 29 and 30 showed that all samples have dominance of meaty, browned, juicy and livery attributes during the mastication period, and then oxidized thereafter. Meaty was the first dominant sensation in all samples with the dominance rates starting at over 50% dominance rate and then decreasing to chance level within 5 s. Dominance of the browned attribute reached significance in the first 3-5 s. Starting from 10 s, oxidized became the dominant attribute above significance level until the end of mastication (except for K-C7 (2), K-P7 (4), L-C7 (6), R-C0 (9), Rib-C0 (13) Rib-P7 (16), Sk-C7 (18), Sk-P7 (20), and Sd-P0 (23) where oxidation became dominant only after 10 s. The attributes livery and juicy were occasionally above significant level, and only lasted a few seconds.

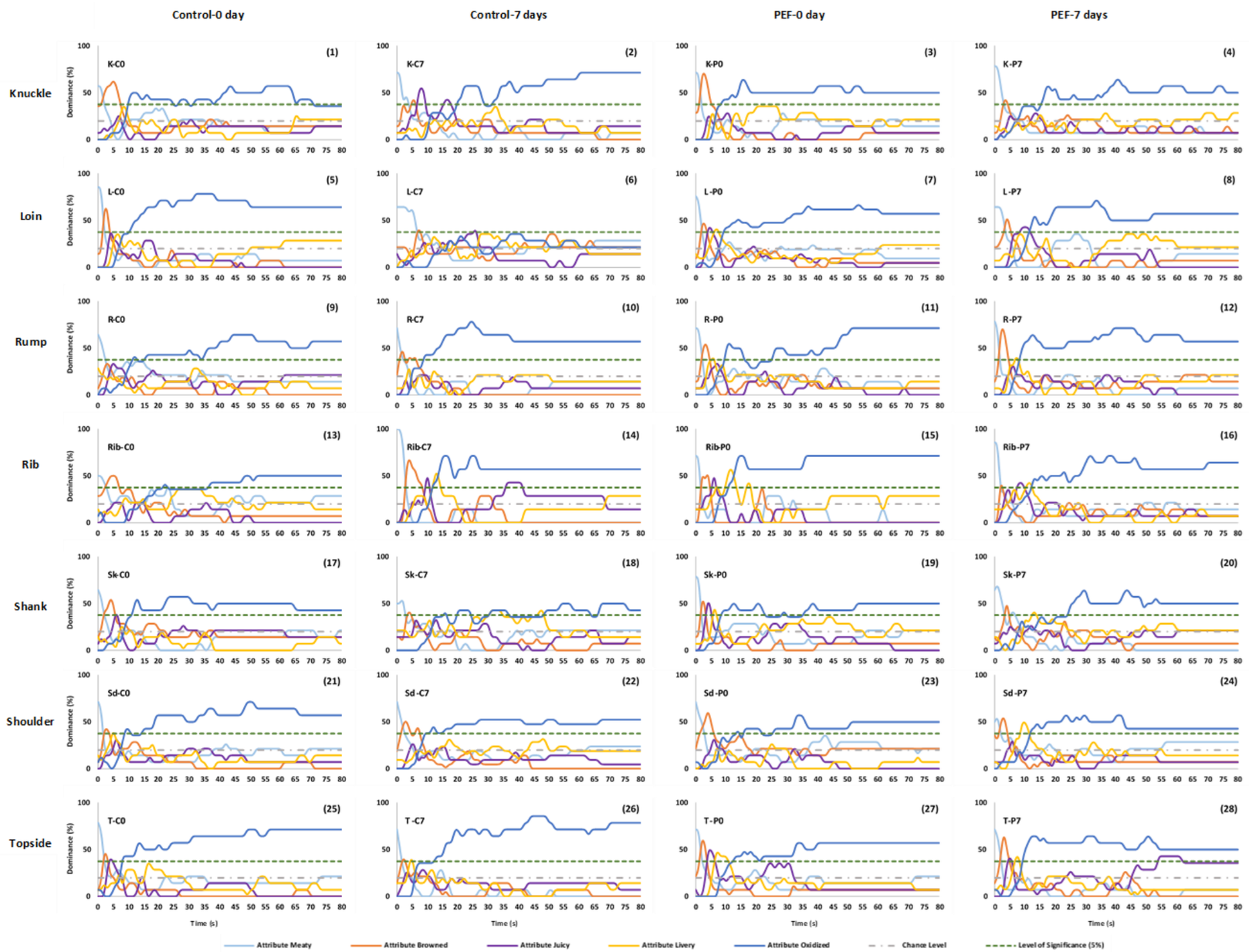

Figure 29 TDS curves for sensory attributes of non-PEF and PEF treated cooked chilled lamb meat of different cuts (C: control; P: PEF; 0 and 7: number of storage days)

Fig. 29 shows TDS curves for sensory attributes of chilled treated lamb samples of different cuts. In the knuckle cut (1-4), meaty started at around 70% dominance rate (except for K-C0 (1)), and then decreased to below chance level at 5 s. Only K-C0 (1) and K-P0 (3) samples were dominant in browned attribute for a short time between 2-7 s and achieved to 60 % and 65 % dominance rate at 5 s respectively. Juicy was only significant in K-C7 (2) sample. Oxidized became significant in almost all samples from 10 s onwards except for K-C7 (2) that was dominant in oxidized attribute only after 20 s. Interestingly, juicy was dominant in K-C7 (2) sample between 7-10 s and 17-19 s. In loin cuts (5-8), almost all samples were dominant in browned attribute for a short time between 2-5 s except for L-C7 (6) sample. Almost all loin cuts were dominant in oxidized attribute after 10 s thereafter except for L-C7 (6) sample that was not dominant for oxidized. The browned attribute was dominant in almost all rump cuts except for R-C0 (9), with a maximum 70% dominance rate at 3 s in R-P7 (12) only. Oxidized became dominant in rump cuts after 10 s onwards, except for R-C0 (9) where oxidation became dominant only after 16 s. In rib cuts, meaty was dominant above significance level in the first 3 s. The browned attribute then became dominant from 5 until 10 s, except for Rib-P7 (16) that did not reach significance level for this attribute. Juicy was not present in Rib-C0 (13) sample but was dominant in Rib-C7 (14), Rib-P0 (15) and Rib-P7 (16) samples between 9 and 11 s. Similar to juicy, livery was dominant in Rib-C7 (14) and Rib-P0 (15) above significance levels. Oxidized then became dominant above significance levels in almost all rib samples except for Rib-C0 (13) from 12 s onwards. Shank cuts were dominant in browned attribute between 2-5 s above significance level except for Sk-C7 (18). Oxidized was significant in all shank cuts that became dominant from 10s, except for Sk-P7 (20) when oxidized became dominant after 25s. In general, dominance of the oxidized attribute was generally less than 50% for all samples. As for shoulder cuts, meaty started at around 70% dominance rate for the first 3 s except for Sd-P7 (24). Browned became dominant from 3-8 s above significance level for almost all shoulder samples except Sd-C0. Similar to shank cuts, dominance

of the oxidized attribute was generally less than 50% for almost all shoulder samples except for Sd-C0 (21). In topside cuts, browned was dominant in T-P0 (27) and T-P7 (28) samples with over 55% dominance rate between 3 and 8 s. Juicy and livery were dominant in T-P0 (27) and T-P7 (28) samples but less than 50%. Oxidized was significant in all topside samples between 8 and 15s. Dominance of T-P0 (27) and T-P7 (28) were just above 50% or less compared to control samples.

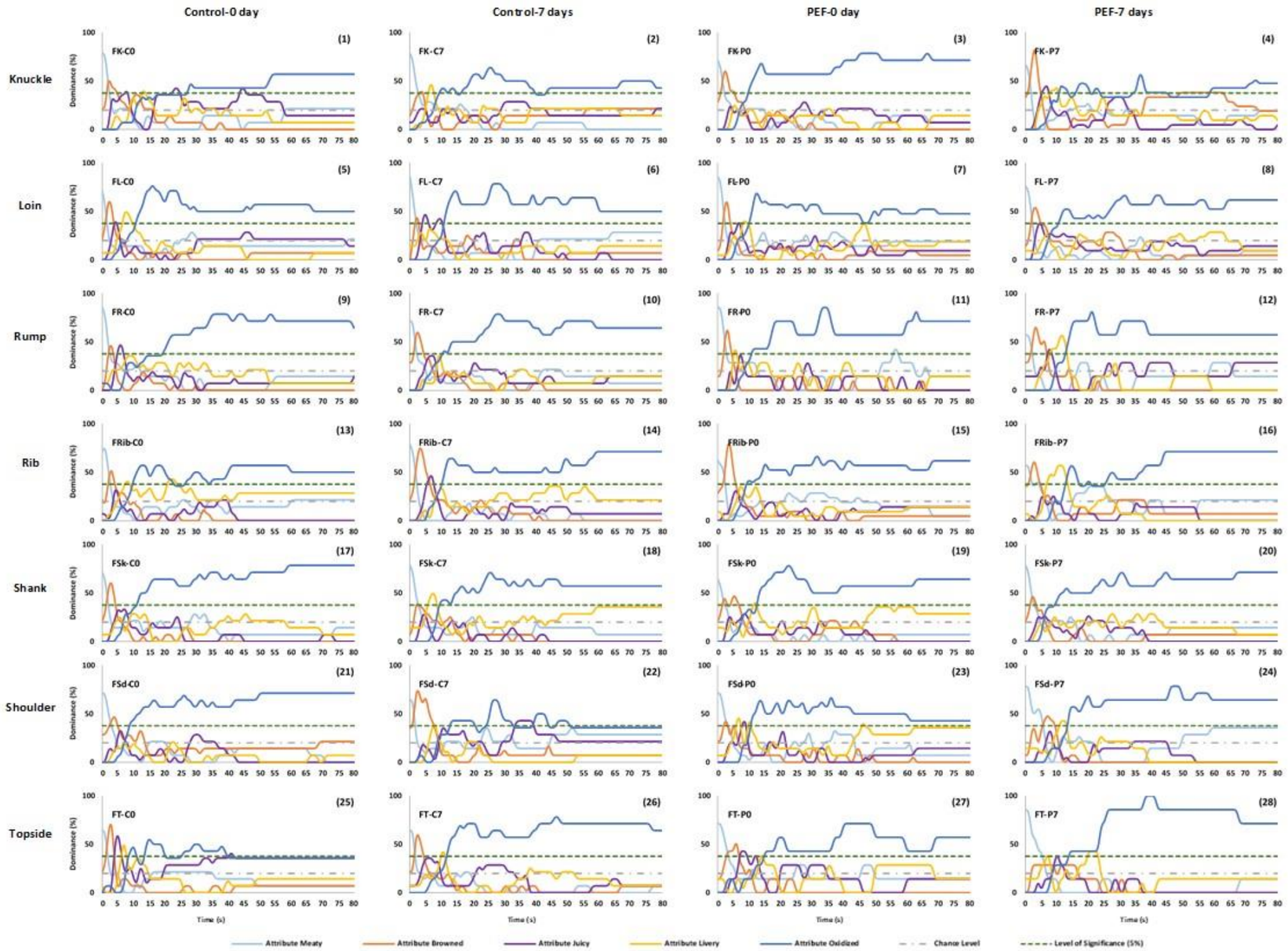

Figure 30 TDS curves for sensory attributes of non-PEF and PEF treated cooked frozen-thawed lamb meat of different cuts (C: control; P: PEF; 0 and 7: number of storage days)

Fig. 30 shows the TDS curves for sensory attributes of frozen-thawed lamb samples of different cuts. In knuckle cut (1-4), meaty was the most dominant at the start of mastication in FK-C0 (1), FK-C7 (2) with 80% dominance rate and FK-P0 (3), FK-P7 (4) with 70% dominance rate, respectively. Browned was dominant in almost all knuckle samples (except FK-C7 (2)) between 2 and 5s and FK-P7 (4) had higher (80%) dominance rate compared to others. The livery was only dominant in FK-C7 (2) and FK-P7 (4) samples, between 6 and 8 s, and 8 and 10s, respectively. Oxidized was dominant in FK-C7 (2) and FK-P0 (3) from 10s and became dominant after 16s in FK-C0 (1). Oxidized also fluctuated around the significant level in FK-P7 (4). In loin cut (5-8) samples, meaty was dominant in all samples and then dramatically dropped to above chance level at 2 s. Livery was only dominant at 9 s in FL-P0 (7) sample. Juicy in FL-C7 (6) sample was dominant from 4 to 10 s and then dropped to above chance level. In rump cuts (9-12), browned attribute in FR-C0 (9), FR-C7 (10) and FR-P0 (11) samples was dominant from 3 to 5 s. It can be seen that the browned attribute in FR-P7 (12) (3.0-8.0s) had longer duration compared to other rump cuts. Juicy was only dominant in FR-C0 (9) and FR-P7 (12) samples between 5 and 8 s. In addition, livery was only dominant in FR-P7 (12) between 5 and 12s. For all rib cut samples (13-16), meaty was the most dominant at the start of mastication and then decreased to below chance level in the first 10 s. FRib-C7 (14) sample was only significantly dominant in juicy attribute from 5 to 10 s. Livery was only dominant in FRib-P7 (16) sample from 8 to 15 s. The oxidized attribute became dominant at 10 s in FRib-C0 (13) and FRib-C7 (14) samples, while in FRib-P0 (15) and FRib-P7 (16) samples oxidized became dominant at 12s. For shank cut (17-20) samples, browned attribute in FSk-C0 (17) and FSk-P7 (20) samples were dominant from 2 to 4 s. It can be seen that the browned attribute in FSk-P0 (12) (2.0-7.0s) had a longer duration compared to FSk-C0 (17) and FSk-P7 (20) samples. Livery was only dominant in FSk-C7 (18) sample from 5 to 8s. In the shoulder cut samples (21-24), meaty was initially dominant until 3 s. However for FSd-P7 (24) sample, meaty was additionally 2 s longer (0-5.4 s). Browned attribute in FSd-C0 (21) and FSd-C7 (22)

samples was dominant from 3 to 5 s. It can be seen that the browned attribute FSd-C0 (21) and FSd-P0 (23) (1.7-3.0 s) lasted for a shorter duration compared to FSd-C7 (22) (0.8-7.5 s) and FSd-P7 (24) (5.2-9.2 s) samples. Livery was only dominant for FSd-P0 (23) and FSd-P7 (24) samples, from 6 to 7s and 10-12s, respectively. Oxidized was dominant in FSd-C0 (21) and FSd-C7 (22) samples that increased at 9 s and remained stable thereafter with small fluctuations until the end of mastication. However, FSd-P0 (23) and FSd-P7 (24) oxidized increased in dominance after 12 s, and in FSd-C7 (22) sample dropped to just below significance level after the 50s. In topside cut (25-28), meaty attribute in FT-C0 (25), FT-C7 (26) and FT-P0 (27) samples was dominant from 0 to 4 s. It can be seen that the browned attribute in FT-P7 (28) (0-6.0s) had longer duration compared to other topside samples. Browned attribute was significant in FT-C0 (25), FT-C7 (26) and FT-P0 (27) between 2 and 5s. The juicy attribute was only dominant in FT-C0 (25) and FT-P0 (27) between 4-7s and 6-9s. The livery attribute was not detected in FT-P0 (27). Oxidized in FT-C0 (25) was dominant between 6 and 40s, which was at least 35s shorter in duration compared to FT-C7 (26) (10.0-80.0s), FT-P0 (27) (15.0-80.0s) and FT-P7 (28) (12.0-80.0s).

Canonical variate analysis.

In this study, Panel Dominance Curves generated from the TDS procedure illustrate the temporal flavor changes of meat sample during consumption. However, the dominance curve only indicates the % of panel agreement, which corresponds to the number of panels selecting the attribute at a given time and does not measure intensity. In addition, as all Panel Dominance Curves (Fig. 29 and 30) showed that the oxidized attribute was the most agreed attribute throughout consumption, the curves did not provide clear discrimination between samples for this attribute. Therefore, discriminant analysis using canonical functions, Canonical Variate Analysis, was used for clearer interpretation of results. Prior to CVA, the sensory attributes in TDS were converted to TDS scores, taking into account the duration and the

intensity selected during TDS trials (Labbe et al., 2009). CVA in this study allowed us to explore the relationships between groups of variables in a data set, which in this case was the sensory attributes in TDS (browned, oxidized, etc.), whilst taking into account the intensity of each selected attributes, the duration of each attributes selected, and its relationship with meat samples on a 2-dimensional map. CVA was carried out for the duration of dominance per attribute, and the 90%-confidence ellipses indicate the proportion of panelist who selected the attribute as dominant at a given time. Both chilled (Fig. 31) and frozen-thawed (Fig. 32) samples were discriminated by CVA with a high variance for sensory data of 94.00% and 90.45% respectively

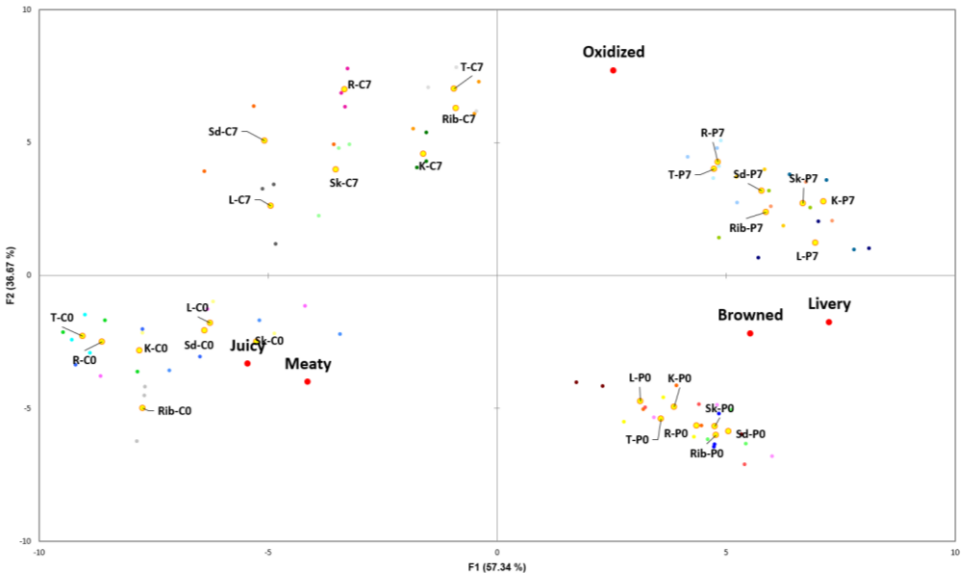

Figure 31 CVA Biplot of dominance durations of sensations of PEF and non-PEF treated cooked chilled lamb meat of different cuts.Hotelling-Lawley trace MANOVA test showed significant product differences (F= 29.655; p < 0.05) based on sensory attributes. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; S=Shank; T=Topside; C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage.

For the chilled meat samples (Fig. 31), Hotelling Lawley MANOVA (F = 29.655; p<0.01) showed significant differences between the samples in terms of the temporal flavor attributes measured by TDS. F1 explained 57.34% of the variance, separating the meat samples in terms of PEF processing, where negative scores of the CVA corresponded to control non-PEF samples, and positive scores corresponded to PEF treated samples. F2

(36.67%) further distinguished between the 0 and 7 days storage meat samples. Positive scores of F2 corresponded to 7 days storage samples, while negative scores corresponded to 0 day storage samples. Samples stored for 7 days were correlated with oxidized flavor. In contrast, control samples (non-PEF) at 0 day was positively correlated with meaty and juicy. PEF treated 0-day samples were correlated with browned and livery attributes.

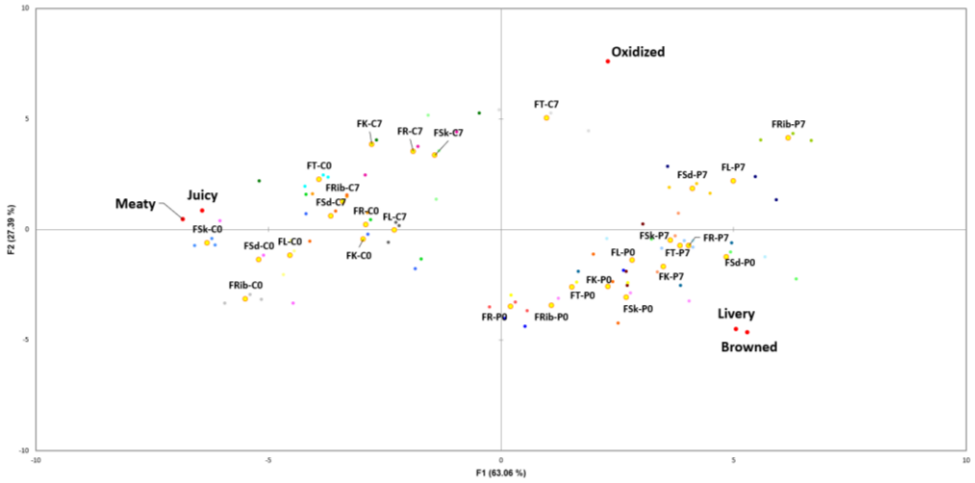

Figure 32 CVA Biplot of dominance durations of sensations of PEF and non-PEF treated cooked frozen-thawed lamb meat of different cuts. Hotelling-Lawley trace MANOVA test showed significant product differences ($F = 29.655$; $p < 0.05$) based on sensory attributes. Sd=Shoulder; Rib=Rib; L=Loin; K=Knuckle; R=Rump; S=Shank; T=Topside; F: frozen; C: control; P: PEF; 0= 0 day storage; 7= 7 days storage/post-processing storage.

For frozen-thawed samples (Fig. 32), Hotelling Lawley MANOVA ($F = 19.256$; $p<0.01$) also showed significant differences similar to chilled meat samples. F1 explained 63.06% of the variance; separating the meat samples in terms of PEF processing treatment, where negative scores of the CVA corresponded to control (non-PEF) samples (except FT-C7), and positive scores corresponded to PEF treated samples. F2 (27.39%) further distinguished the almost all lamb samples between the 0 and 7 days storage. Positive scores of F2 were associated with 7 days storage samples (except FT-C0 and FR-C0), while negative scores were associated with 0 days samples (except FR-P7, FSk-P7, FT-P7, FSd-P0 and FK-P7). Samples treated with PEF was correlated with oxidized flavor, especially FRib-P7. In contrast, control samples (non-PEF) was positively correlated with meaty and juicy, especially

at 0-day storage. PEF treated 0-day samples were correlated with browned and livery attributes.

4.4.3. Conclusion

Initial tenderness of both chilled and frozen-thawed meat were not affected by PEF processing and storage. PEF treatments affected the temporal flavor profiles of meaty and oxidized flavor attributes. A longer storage period was associated with oxidized flavour. PEF treatments of all chilled and frozen cuts were associated with browned and livery flavor attributes. In addition, PEF processing contributed to a more oxidized flavor in PEF treated frozen – thawed rib cut when stored for 7 days. These results imply that type of sample pre-treatments (chilled or frozen-thawed), type cuts, as well as storage are important factors to consider when applying PEF treatments to lamb meat. All frozen-thawed lamb meat cut not suitable for PEF treatment.

Chapter 5. General Discussion

Based on export data from Beef & Lamb (2018), 41% and 10 % of chilled sheep meat are exported to the UK and USA respectively, while 44% and 12 % of frozen sheep meat are exported to China and the UK respectively. Export of chilled meat has become constant, but frozen sheep meat continues to be in big demand in the China market. As consumers are the final target for the meat production chain, their expectations of meat and meat products directly impact on the profitability of the meat industry. Hence it is important to have a good understanding of consumer perception and purchase intentions of meat and its products. The first aim of this research was to gain a better understanding of important lamb meat attributes that influenced consumer perception and purchase behavior (Section 4.1).

The meat processing industry is always looking for emerging technologies, which can inactivate microorganisms at near-ambient temperatures, avoid thermal degradation of the meat components, and preserve the sensory and nutritional qualities of meat products. Hence the other aims of this research were to explore how non-thermal processing methods like HPP and PEF can be applied to improve lamb meat quality. As discussed in the literature review the two non-thermal proccessing technologies that have been applied to meat are high pressure processing (HPP) and pulsed electric field (PEF) processing. The effects of HPP and PEF treatments on the physicochemical and sensory qualities of different lamb meat cuts are discussed in Sections 4.2, 4.3 and 4.4.

The first major finding in Section 4.1 was that Chinese consumers are willing to pay more money to purchase imported lamb meat because they believed it to be high quality in terms of taste, texture and safety. Maria Font-i-Furnols & Luis Guerrero, (2014) stated that tenderness, juiciness and taste of meat were highly associated with purchase intention. Furthermore, Banović, Grunert, Barreira, & Fontes, (2009) concluded that appearance

characteristics like colour, visible fat, and degree of marbling determine consumers' expectations of meat quality. The second major finding was that Chinese consumers found that tenderness, followed by colour and flavor were important quality attributes when purchasing lamb meat. Furthermore, Chinese consumers consumed a variety of lamb meat cuts cooked with different methods like hotpot, pan frying, stewing and barbecuing. The different methods of cooking methods utilise different meat cuts. Hence it is not necessarily high value prime cuts like the loins and legs that Chinese consumers favour. Thus there exist a great potential to market low value cuts of lamb meat for the Chinese market. It was also found that consumers demand high quality, convenient, innovative, and safe meat products with natural flavour and taste, and an extended shelf-life. To meet all these demands without compromising safety, the production and manufacture of meat products have stimulated research concerning the development and implementation of alternative technologies that are quicker and milder than traditional thermal technologies (Aymerich, Picouet, & Monfort, 2008). Novel non-thermal technologies such as HPP and PEF, have the ability to inactivate microorganisms at near-ambient temperatures, avoiding thermal degradation of the food components, and consequently preserving the sensory and nutritional quality of the fresh-like food products (Pereira & Vicente, 2010). Studies have also shown that both HPP (Toepfl, Mathys, Heinz, & Knorr, 2006) and PEF (Lung, Masanet, & McKane, 2006) contribute lower energy consumption and more energy savings to the food industry. Therefore, in this study HPP and PEF technologies were selected to explore their impact on physicochemical and sensory qualities of different lamb meat cuts.

Studies have demonstrated that HPP influenced the quality parameters of meat, such as colour changes in beef (Jung, Ghoul, & de Lamballerie-Anton, 2003), and lipid oxidation in chicken breast (Beltran, Pla, Yuste, & Mor-Mur, 2003). Only McArdle, Marcos, Mullen, & Kerry (2013) reported the influence of HPP conditions (200 MPa, 400 MPa, and 600 MPa) on selected lamb

brisket quality attributes and their stability during chilled storage. Therefore, the second study in this research investigated the effects of HPP on frozen lamb cuts at varying pressure levels between 200 MPa and 600 MPa on the physicochemical and sensory qualities of the lamb meat (Section 4.2). Three lamb muscles with different tenderness levels were selected (loin>shoulder>shank). The effects of HPP at varying pressure levels on low value lamb meat cuts like shank or shoulder were investigated. In general, the increased pressure level can enhance the chemical and enzymatic reaction in meat. Proteolysis is active at lower pressure (200 MPa and 300 MPa), and can contribute to tenderness at higher pressures (400MPa and 600 MPa). However, proteolytic activity and colour changes may occur at these pressure level. The results showed that HPP significantly affected physicochemical properties and sensory characteristics of the three different lamb cuts. TBARS value significantly increased as pressure increased from 300 MPa, and the higher levels of pressure (400 MPa and 600 MPa) resulted in higher oxidation values in shank, loin and shoulder cuts of lamb. Lipid oxidation has been reported to occur with HPP treatment due to: 1) accessibility of iron from hemoproteins that increases with disruption of membrane; 2) iron released from hemoproteins facilitate lipid oxidation (Bajovic, Bolumar, & Heinz, 2012). These mechanisms may help explain the significant increase in lipid oxidation observed in samples processed particularly at higher pressures. Increased lipid oxidation after HPP, may be due to conformational changes of hemoproteins, which results in greater exposure of the catalytic heme group to unsaturated fatty acids (Bou et al., 2008). This was supported by fatty acid results in this study that showed total PUFA content significantly decreased in shank and shoulder cuts after HPP treatment at 200 MPa and 300 MPa, respectively compared to control samples. With respect to individual fatty acids, the significant changes in PUFA were mainly due to changes in C18:1n9 and C18:2n6 content. On the other hand, higher TBARS value at higher pressure levels (400 MPa and 600 MPa) also resuted in significant colour changes in this study. The L* value of shank, loin and shoulder cuts were significantly increased when treated at

200 MPa, 300 MPa 400 MPa and 600 MPa compared to control samples of the corresponding cuts. The "whitening/brightening" effect of pressure could be attributed to denaturation of globin, release of haem, and oxidation of ferrous to ferric myoglobin at pressures more than 400 MPa (Campus, Flores, Martinez, & Toldrá, 2008). However, meat discoloration could be a problem when marketing pressurized raw meat, as meat colour is one of the most vital criterion for consumers when purchasing meat.

Interestingly, the total free amino acids of HPP treated samples were higher than control lamb meat cut. This is because increased pressure level can enhance the chemical and enzymatic reaction. Free amino acids may influence brothy and meaty flavours that are known precursors of meat flavour (Suzuki et al., 1994). Therefore a high concentration of free amino acids in HPP treated samples may influence meat flavour. The Maillard reaction occurs between reducing sugars and free amino acids when heated (Koutsidis et al., 2008; Mottram, 1998). Therefore, changes in the temporal sensory attributes of HPP processed lamb were investigated (Section 4.2). In this study, Temporal Dominance of Sensations (TDS) was used to allow panellists to continually indicate the dominant attribute changes over time (Pineau et al., 2012). TDS results showed that HPP processing affected the temporal flavour profiles meat samples. Samples treated at high pressure levels of 400 and 600 MPa were associated with browned, livery and oxidized flavours. These results imply that when carrying out HPP processing of meat, it is important to consider the pressure levels applied and the type of meat cuts used to achieve a product with desirable physical, chemical and sensory characteristics. Shank and shoulder lamb cuts subjected to pressures of 200 and 300 MPa, and loin cut treated at 200 MPa have meaty and juicy attributes similar to the control sample. Oxidized attribute was correlated higher levels of pressure (400 MPa and 600 MPa), which may be due to lipid oxidation. The higher levels of pressure (400 MPa and 600 MPa) also resulted in higher oxidation values in shank, loin and shoulder cuts of lamb. In addition, shank cut treated at 600 MPa was correlated with livery.

Livery flavor is a complex trait that cannot be related to any single characteristic (Yancey et al., 2006). Livery flavor in this study may be attributed to the high free amino acids produced when treated at 600 MPa, Methionine is an important precursor of sulphur volatile compounds meat that may interact with carbonyl compounds to produce the livery flavor attribute in pork (Mussinan & Walradt, 1974), beef (Werkhoff et al., 1996) and lamb (Lorenz et al., 1983) liver. These results showed that HPP technology could potentially be applied as a pre-treatment for obtaining prepared "ready" meals, when pressure levels under 300 MPa were applied on low value cuts (shank and shoulder).

Studies conducted on the use of PEF in muscle foods (especially in beef) have shown that muscle cell permeability can be enhanced due to electroporation and consequently enhance proteolysis that contributes to tenderisation (Bekhit, van de Ven, Suwandy, Fahri, & Hopkins, 2014; Suwandy, Carne, van deVen, Bekhit, & Hopkins, 2015; Jaeger, Balasa, & Knorr, 2008; Toepfl, Heinz, & Knorr, 2007). Proteolysis can influence the quality characteristics of meat during processing (such as aging and dry-curing), and is an important source of flavour compounds (free amino acids and small peptides). Studies have also found that aging meat prior to freezing can increase tenderness and minimize drip loss in beef (Kim et al., 2011), lamb (Choe, Stuart, & Kim, 2016) and venison (Wiklund, Farouk, Stuart, & Dobbie, 2009). However, meat quality changes can change in frozen/thawed meat (Li & Sun, 2002). Leygonie, Britz, & Hoffman (2012) reported that the formation of ice crystals during freezing not only causes physical and structural damages to muscle tissues, but can also lead to various changes in lipid oxidation, fatty, acids and volatile composition. However, only Faridnia et al (2015) investigated the effects of freezing as a pre-treatment prior to PEF treatment on the physicochemical characteristics of *semitendinosus* beef muscle. They found that frozen-thawing initiated primary lipid oxidation in the meat. This can lead to radical secondary lipid oxidation upon thawing, leading to adverse changes in colour, flavour and nutritional value (Leygonie et al., 2012).

Therefore, the final two Sections of my research was to determine how PEF treatment affects physicochemical and sensory qualities of seven different lamb meat cuts and how pre-treatments (freezing) prior to PEF processing affect the quality attributes of seven different lamb meat (Sections 4.3 and 4.4).

This is the first study that investigates the impact of PEF treatments on lamb meat qualities of seven lamb muscles. Three high value cuts (loin shoulder and rib) and four low value cuts (shank, knuckle, rump and topside) were selected for PEF treatments. PEF parameters were electric field strength 1-1.4 kV/cm, pulse width 20 µs, frequency 90 Hz and total specific energy 88-109 kJ/kg. The application of PEF with a sufficiently high electric field strength can affect muscle cell membranes due to changes in their transmembrane potential (Suwandy et al. 2015; Bekhit et al. 2014). Generally, electroporation occurs when the electric field strength exceeds the threshold value of the transmembrane potential. When the overall potential exceeds 0.5 kV/cm electric field strength in animal cells, electroporation occurs leading to transient increase of membrane permeability (Alahakoon, Faridnia, Bremer, Silcock, & Oey, 2016), and accelerate the activities of proteolytic enzymes in meat. PEF treatment in combination with aging have an additional effect on meat tenderness due to an increased rate of proteolysis (Faridnia et al. 2015). Ageing is a slow and time-consuming process that requires a period of up to 14 days and is expensive owing to the need for long refrigerated storage times (Herrera-Mendez et al., 2006). Martínez-Cerezo, Sañudo, Medel, & Olleta (2005) concluded that 4 days of ageing seems to be enough to obtain high quality lamb meat. As this is the first study of lamb meat on PEF treatment in combination with aging, 7 days ageing storage was inveistigated. The results in Sections 4.3 and 4.4 showed that PEF significantly affected physicochemical properties and sensory characteristics of the three different lamb cuts. PEF processing affected lipid oxidation in chilled and frozen-thawed meat, but did not lead to off-flavour in chilled meat. This may

due to freezing and thawing of meat that can accelerate TBARS accumulation and generate pro-oxidants, especially the haem iron (Benjakul & Bauer, 2001). Results from fatty acids analysis (Section 4.3.5) supported lipid oxidation results (section 4.3.3). Total PUFA content significantly decreased in chilled and frozen-thawed rib, rump and shank cuts after PEF treatment compared to control samples. The increase in total free amino acids was higher in PEF treated chilled topside and knuckle cuts, and frozen-thawed rump and shoulder cuts stored for 7 days compared to the non-PEF treated samples of the corresponding cuts. As the degradation products derived from lipid and protein oxidation are evident, the volatile profiles of samples subjected to PEF treatment were further determined.

A total of 24 volatiles that comprised of 1 alcohol, 3 ketones, 7 aldehydes, 3 furans and 10 nitrogen- and sulfur-compounds were found in the headspace of cooked lamb meat using the SPME–GC–MS method (Section 4.4). Hexanal and heptanal were significantly higher in PEF treated chilled (rump, rib, shank and shoulder) and frozen-thawed (knuckle, loin, rump, rib and shoulder) lamb cuts. Hexanal is mainly generated during the oxidation of linoleic acid (Purriños, Franco, Carballo, & Lorenzo, 2012). This was suported by the higher TBARS value found in PEF treated samples (Section 4.3). Heptanal was generated from the oxidized oleic acid in beef fat (Machiels, Istasse, & Van Ruth, 2004). 3-methyl butanal and 2-methyl butanal were significantly higher ($p< 0.05$) in PEF treated chilled (knuckle, shank and shoulder) and frozen-thawed (knuckle and rib) cuts. These volatiles are Strecker degradation products (Mottram, 1998), which are formed by leucine. 3-methyl butanal contributed to roasted beef flavor (Machiels et al., 2004). Temporal dominance of sensations (TDS) results showed that both storage and PEF treatments affected the temporal flavor attributes of meaty and oxidized flavor(section 4.3). A longer storage period was associated with oxidized flavor, while PEF treatments for all chilled and frozen cuts were associated with browned and livery flavor attributes. Furthermore, PEF processing contributed to more oxidized flavor in PEF treated frozen–

thawed rib cut stored for 7 days. These results imply that type of sample pre-treatments (chilled or frozen-thawed) and cuts, as well as storage are important factors to consider when applying PEF treatments to lamb meat.

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Chapter 6. Conclusion, Limitations & Future Opportunities

6.1. Conclusion

This study clearly shows that non-thermal processing methods like HPP and PEF can be applied to improve lamb meat quality. The first aim of this study was to determine factors that influenced perception and purchasing behaviour of lamb meat by Chinese consumers. Freshness, flavour, texture, safety and nutrition influenced purchasing behaviour of meat. Chinese consumers are also willing to pay more money to purchase imported lamb meat, because they valued high quality. Chinese consumers also consumed different lamb meat cuts cooked in different ways. Hence it is important for the meat industry to establish clear market targets for Chinese consumers in terms of quality requirements, type of meat cuts, regional markets and season when meat is consumed.

The second aim of this study is determined how HPP treatment affects physicochemical and sensory qualities of three different lamb meat cuts. HPP significantly affected physicochemical properties and sensory characteristics of the three different lamb cuts. Lamb meat discoloration, lipid oxidation changes in sensory properties occurred when HPP was applied at higher pressure levels. Fatty acids and free amino acids content varied in different meat cuts with increase in pressure levels. These results imply that when carrying out HPP, it is important to consider the pressure levels applied and the type of meat cuts used to achieve a product with desirable physical, chemical and sensory characteristics.

The final aim of this study was to determine how different freezing pre-treatments prior to PEF affects physicochemical and sensory qualities of seven different lamb meat cuts (Sections 4.3 and 4.4). It was obvious that

PEF significantly affected physicochemical properties and sensory characteristics of the seven lamb meat cuts. There were less PEF effects on cooking loss when applied to frozen-thawed meat compared to chilled meat samples. PEF processing influenced the fatty acids profile of the different chilled and frozen-thawed lamb cuts. For chilled meat, PEF treatment only influenced the free amino acids profiles of rump, loin and rib cuts. However with frozen-thawed meat, free amino acids increased with increased storage time. PEF treatments also affected the temporal flavour profiles of meaty and oxidized flavour attributes. PEF processing contributed to a more oxidized flavour in PEF treated frozen–thawed rib cut when stored for 7 days. These results imply that type of sample pre-treatments (chilled or frozen-thawed), type cuts, as well as storage are important factors to consider when applying PEF treatments to lamb meat.

6.2. Limitations & Future Opportunities

- Chilled and frozen-thawed lamb meat were obtained from different sources due to logistic issues. In this study, frozen-thawed lamb meat samples were obtained from Agresearch (Hamilton) and delivered to Auckland. As the PEF facility was located at University of Otago (Dunedin), chilled meat waspurchased from a local supermarket in Dunedin. As all physical, chemical and sensory analysis were carried out on chilled and frozen-thawed lamb meat from different sources, it was not possible to make comparisons between chilled and frozen-thawed lamb meat results to understand the influence of freezing and thawing pre-treatments prior to PEF processing on lamb meat quality. Hence further effects of freezing and thawing pre-treatments should be carried out on meat samples from the same source.
- Freezing and thawing conditions were also not considered in this study and should be investigated in further studies. In general, the quality of frozen food is closely related to freezing and thawing processes. The rate of freezing and the formation of small ice crystals

in freezing are critical to minimise tissue damage and drip loss in thawing (Li & Sun, 2002). Thawing generally occurs more slowly than freezing. During thawing foods are subject to damage by chemical and physical changes and microorganism. Freezing and thawing affect meat quality attributes such as moisture, colour, tenderness and oxidation of lipids and protein. In order to better understand the effect of PEF on frozen-thawed meat quality, the frozen thawing procedures should be optimized to minimize effects of freezing and thawing on meat quality prior to PEF treatment.

- Electric field strength, frequency, and specific energy as PEF parameter were only considered in this study. Further experiments should be carried out to optimize the effect of important PEF parameters that influences meat quality by using central composite design (CCD). These parameters are important to the increasing efficiency in microbial and enzymatic inactivation by PEF application.
- In this study, the effect of PEF processing was only investigated on the quality of post-rigor (cold-boned) lamb meat at 0 and 7 days of storage. The muscle response to PEF treatment can however vary depending on whether the muscles are pre-rigor (hot-boned) or post-rigor (cold-boned). As the skeletal framework is absent, hot-boned meat is more susceptible to subsequent contraction and shortening than meat that is cold boned. Therefore, hot-boned meat is usually tougher than cold-boned meat. However, to a certain extent, hot-boned meat is useful for PEF as each muscle is separated in the pre-rigor state which enables the muscles to be manipulated prior to the onset of rigor (Alahakoon et al., 2016). This enables different PEF intensities to be used for each muscle to achieve optimal results (Bekhit et al. 2016). Hence it would be of interest to determine PEF affects the quality of lamb meat from hot-boned lamb meat muscles at various ageing times.
- For the meat industry, the greatest limitation in the application of both HHP and PEF technologies are the high initial capital

investments and the cost involved in changing the plant design are highly prohibitive (Jeyamkondan et al. 1999). Research results to date suggest that PEF has a significant role to play in the meat industry for specific applications such as improving the tenderness and value of tougher cuts of meat and in enhancing mass transfer and reducing processing time and cost. PEF cannot offer even treatment distribution in non-uniform and complex food matrices such as meat. It will be particularly challenging under the factory settings for bone-in meat cuts with variations in fat content to be PEF processed as these cuts comprise of non-uniform tissues that result in unevenly treated product with variations in effective electropermeabilization. The non-homogenous distribution of the electric field was demonstrated by Golberg et al. (2015) who observed less than 40% of the PEF strength in the cells near vascular structures in a rat liver due to the formation of “electric fields sinks”. For PEF technology to be implemented in the meat industry, all parts of the meat cuts should achieve a permeabilization level that contributes to tenderization. Currently, all published reports available on application of PEF have used almost homogeneous meat samples devoid of fat and bones. Hence PEF can only find application in lean muscles and therefore, a great deal of research is still needed before a commercial system becomes a reality.

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Appendices

Appendix Ⅰ. Compilation of studies on the effect of HPP on the quality characteristics of meat

Appendix Ⅱ. Application of researches on the effect of PEF on the quality characteristics of meat and meat product

Appendix Ⅲ. Application of TDS on meat and meat products

Appendix Ⅰ. Compilation of studies on the effect of HPP on the quality characteristics of meat

Food product	HPP parameters	Application	Main findings	Measurements	References
Minced pork	800 MPa for 20 min at 20°C prior to storage at 4°C.	Lipid oxidation	High pressure treated samples oxidized more rapidly than the control samples. The rate of lipid oxidation of high pressure treated samples was similar to that induced by heat (80 °C for 15 min). No significant increase in the rate of oxidation was observed in minced meat samples treated at 300 MPa, but above this pressure the rate increased with intensity.	TBARS	Cheah & Ledward (1996)
Turkey thigh muscle	100 MPa, 200 MPa, 300 MPa, 400 MPa or 500 MPa for 10 min or 30 min.	Lipid oxidation	All pressure treatments affected lipid oxidation compared to non-treated meat. Only the most intense pressure treatments (500 MPa for 30 min) resulted in lipid oxidation that was comparable to that induced by heat treatment (100°C for 10 min). Pressure treatment at 400 MPa and lower pressures for 30 min (and for 10 min) resulted in a lower oxidation level.	TBARS	Dissing, Bruun-Jensen, & Skibsted (1997)
Chicken breast muscle	300, 400, 500, 600, 700 or 800 MPa for 5 min or 10min, or to heat treatment (8 to 7 °C for 10 min)	Lipid oxidation	The pressure treatment at 800 MPa for 10min was found to enhance lipid oxidation to the same extent as heat treatment. Pressure treatment at 600MPa and 700 MPa resulted in less oxidation compared to heat treatment. Chicken breast muscle exposed to pressure at or below 500 MPa showed no indication of rancidity, similar to untreated meat during chill storage.	TBARS	Orlien, Hansen, & Skibsted (2000)
Chicken breast	300 and 500 MPa for 30 min at 20°C;Cooked (90 °C for 15 min	Lipid oxidation	Increased lipid oxidation level with increased pressure. Generally, pressurized samples had fewer oxidation compounds than cooked samples. Compared to traditional thermal processing (90°C, 15mins), non-thermal processing (300 and 500MPa 30mins in HPP at 20°C) resulted in little change in the nutritional value of meat products.	TBARS	Beltran, Pla, Yuste, & Mor-Mur (2003)
Beef and chicken muscles	200MPa,400MPa, 600MPa and 800 MPa; 40°C 50°C 60°C and 70°C, for 20mins	Lipid oxidation	The increase in lipid oxidation values was more marked after treatment at pressures ≥400 MPa than lower pressures in beef. Pressure treatments of 600 MPa and 800 MPa increased rates of lipid oxidation in chicken muscle. Oxidative stability of minced chicken breast muscle was not affected by pressures up to 500 MPa and this was believed to be related to the integrity of the cell membrane.	TBARS	Ma, Ledward, Zamri, Frazier, & Zhou (2007)

Food product	HPP parameters	Application	Main findings	Measurements	References
Pork loin (*M. longissimus dorsi*)	HPP of 215MPa for 15s with water temperature at 33°C	Postmortem metabolism Pork quality	HPP inhibited the rate of lipid oxidation in ground pork samples. This might due to the low pressure (215Mpa) employed.	Texture Analyzer, Sensory evaluation, Warner–Bratzler, shear force, TBARS, Colour,	Souza et al (2011)
Lamb (*M. pectoralis Profundis*)	20mins at 200,400 and 600 MPa, and temperatures of 20, 40 and 60 °C	Meat quality traits	Samples pressurized at 400 & 600 MPa at 60 °C resulted in the highest TBARS values. The PUFA/SFA ratios of pressurized samples were significantly higher when compared to non-treated samples, with the exception of the milder treatments (20 °C at 200 and 400 MPa). However there were no significant effects on the n6:n3 ratios.	texture, pH, colour, Warner Bratzler, shear force, TBARS	McArdle, Marcos, Mullen, & Kerry (2013)
Korean native black goat	100 MPa for 24h at 20 °C	Chemical properties	Fatty acid content in goat meat was not significantly (P>0.05) different between control and HPP treated samples for all fatty acids detected.	Fatty acids, Volatile compounds	Kang et al (2013)
Beef Rounds	100 to 300MPa for 10mins at 25 °C	Protease Activities	High-pressure treatment modulates the proteolytic activities of meat to improve its quality resulting in increased free amino acid content. Tryptic digestibility of the beef extract was increased at pressures higher than 400 MPa.	Free amino acids	Ohmori, Taji, Shigehisa, Hayashi, & Rikimaru (1991)
Lean beef meat	2°C with ice and water, and Pressure was applied at 100, 150, 200, 300 or 400 MPa for 5 mins	Flavour-related components	No significant differences were observed in the amino acid and peptide content, suggesting that high-pressure treatment had no adverse effect on the components responsible for brothy and meaty flavours, and cooked flavour of the meat.	Free amino acids	Suzuki et al (1994)
Chicken breast fillet	300, 450 and 600 MPa, 5 min, 15 °C	microbial population, meat quality and sensory characteristics	600 MPa inactivated E. coli, S. typhimurium and L. monocytogenes below detectable levels. Increased pressure levels increased the cooking loss and the colour by increasing L*, a*, b* values. Increased pressure increased hardness, cohesiveness, gumminess and chewiness. Pressure level of 450 MPa induced lipid oxidation. Volatile basic nitrogen values (VBN) were significantly reduced. A semi-trained sensory panel found that chicken breast treated with 450 MPa gave the lowest aroma strength.	Aerobic plate count, Colour Volatile basic nitrogen, TBARS, Texture Analyzer, Sensory evaluation	Kruk et al (2011)
Chicken breast fillet	300 MPa, 5 min, 20 °C in combination with liquid antimicrobial edible coating and MAP packaging.	Meat quality traits	The combination of antimicrobial coating and HPP in MAP packaging exhibit a strongly synergistic interaction extending the shelf-life up to 28 days. The sensory attributes, color, tenderness and overall acceptability were maintained during storage	Microbiological counts, pH, Colour, TBARS, Cook loss, Warner–Bratzler, shear force, Sensory evaluation	Rodríguez-Calleja, Cruz-Romero, O'Sullivan, García-López, & Kerry (2012)
Beef *(M. pectoralis profundus*)	200, 300 and 400 MPa, for 20 min at 20 and 40 °C	Meat quality traits	Lower pressure levels of 200 MPa minimally affect meat quality parameters. Increasing the pressure level and temperature level increased the cooking loss, lipid oxidation and alter the color. Pressure did not alter the ratio of polyunsaturated/saturated fatty acid (PUFA/SFA), but increasing the temperature affected the sum higher saturated, monounsaturated and polyunsaturated fatty acids. Changes in color were more depending on the applied pressure than on the holding time.	Fatty acids, TBARS, pH, Colour, Microbiological counts	McArdle, Marcos, Kerry, & Mullen (2010)
Beef (*M.longissimus thoracis & gluteus medius*)	3 min at 175 MPa and 2 min at 250 MPa	Meat quality traits	Pre-rigor high-pressure processing of *longissimus thoracis* was effective in improving eating quality within one day. High-pressure processing was more effective than prolonged aging in improving eating quality of *gluteus medius* . High-pressure processing was associated with an increase in ultimate pH.	pH, shear force, Sensory evaluation	Morton et al (2017)

Appendix Ⅱ. Application of researches on the effect of PEF on the quality characteristics of meat and meat product

Food product	HPP parameters	Application	Main findings	Measurements	References
Chicken Meat Salmon	Electric field strength: less than 2 kV/cm, 20–40 pulses 1.36 kV/cm and 60 pulses Pulse width: 2 μs	Microstructure	PEF treatment with low E had an effect on the microstructure: decrease in average cells size for salmon (34%) and chicken (61%) and gaping occurred. The greater effect of PEF on salmon than chicken.	Electron microscopy analysis, Myofibrillar protein Profile	Gudmundsson & Hafsteinsson (2001)
Beef (*M.Triceps brachii*)	Electric field strength: 3.5 kV/cm Frequency : 20 Hz Treatment time: 5 s	Tenderization	A significant decrease of shear force of 21.5%	Shear force, Cooking loss	Lopp & Weber (2005)
Beef (M.Longissimus lumborum & M.semimembranosus)	Repeated pulsed electric field treatment Electric field strength: 10 kV/cm Frequency: 90 Hz Pulse width: 20 μs	Tenderization	3× PEF treatments had reduced the tenderness of hot-boned beef longissimus lumborum muscle, whereas lowest shear force was found in beef semimembranosus muscles. An increase in proteolysis of troponin T was seen to the largest extent with 1× PEF treatment and decreased with every extra application of treatment.	Tenderness, Purge loss, Cooking loss Myofibrillar protein profile, Post-mortem proteolysis	Bekhit et al (2016)
Beef (*M.Semitendinosus*)	Electric field strength: 1.1–2.8 kV/cm Energy density: 12.7–226 kJ/kg Frequency: 5–200 Hz Pulse number: 152–300	Tenderization	PEF affected the myofibrils and induced significant weight loss. PEF had no impact on Hunter colour values and tenderness	Colour, Cooking and Texture analysis, Drip loss, Myofibrils particle size Nuclear magnetic resonance (NMR) relaxation	O'Dowd, Arimi, Noci, Cronin, & Lyng (2013)
Turkey Breast meat	Electric field strength: Up to 3 kV/cm Frequency: 50 Hz Pulse width: 20 μs Pulse number: 300 pulses	Meat quality traits	PEF treatments did not induce any lipid oxidation of the turkey meat assessed across storage in aerobic conditions. Different PEF parameters only affected by texture and odor. The sensory result suggests that the differences produced by PEF processing are fairly subtle.	TBARS, Colour, Purge loss, Cooking loss, Texture, Sensory analysis	Arroyo, Eslami, et al.(2015)

Food product	HPP parameters	Application	Main findings	Measurements	References
Pork (M.Longissimus thoracis etlumborum)	Electric field strength: 1.2, 2.3 kV/cm Energy densities: 22.6-181.1 kJ/kg Electrode gap: 60 mm Pulse width: 20 µs Pulse numbers: 150 or 300 pulses Frequency: 100 or 200	Acceleration of meat salting	Treatments with higher pulse number and lower frequencies lead to greater electroporation as indicated by a trend for increased hardness, cook loss and saline migration.	Texture profile analysis, Weight changes, Cooking loss and water holding capacity, TBARS	McDonnell, Allen, Chardonnereau, Arimi, & Lyng (2014)
Beef (M.Longissimus thoracis)	Electric field strength: 0.2–0.6 kV/cm Frequency: 1–50 Hz Pulse width: 20 µs	Meat quality traits	PEF treatments have led to more porous tissue structure leading to more water loss. pH, colour stability, cooking loss, shear force and protein profile was unchanged by PEF treatments applied.	Purge loss, Colour, Shear force, Cooking loss, Myofibrillar protein Profile, Microstructural analysis	Faridnia, Bekhit, Niven, & Oey (2014)
Beef (M.Longissimus thoracis et lumborum)	Electric field strength: 1.4 kV/cm Frequency: 10 Hz Pulse width: 20 µs Pulse number: 300, 600 pulses Specific energy: 25 and 50 kJ/kg	Tenderization	No detrimental effect on cook loss, storage loss and colour regardless of the length of ageing before PEF application (2, 10, 18 or 26 days post-mortem) PEF showed a "tendency" on reducing toughness of beef samples, but PEF did not affect the tenderization process provided by ageing itself as WBSF values at different times post-treatment was not affected by an early application of PEF	Weight loss and storage loss, Colour, Cooking loss, Warner–Bratzler, Shear force, Sensory analysis,	Arroyo et al (2015)
Beef (M.Longissimus lumborum & M.semimembranosus)	Electric field strength: 5, 10 kV/cm Frequency: 20, 50, 90 Hz	Tenderization	PEF treatment decreased the shear force of both beef muscles by up to 19%. The shear force of beef semimembranosus was dependent on the PEF frequency	Western blotting, Shear force, Myofibrillar protein Profile	(Suwandy et al., 2015a)
Beef (M.Longissimus lumborum & M.semimembranosus)	Repeated pulsed electric field treatment Electric field strength: 10 kV/cm Frequency: 90 Hz Pulse width: 20 µs	Tenderization	The shear force of beef *longissimus lumborum* was found to significantly decrease by PEF. There was an increase in proteolysis of *beef longissimus lumborum* treated with 1× pulsed electric field as evident by increased troponin T and desmin degradation. Physical disruption is responsible for the tenderisation of beef by pulsed electric field.	Myofibrillar protein Profile, Western Blotting, TBARS, Colour, Shear Force, Cooking Loss, Purge loss	Suwandy, Carne, van de Ven, Bekhit, & Hopkins (2015d)

Food product	HPP parameters	Application	Main findings	Measurements	References
Beef *(M. semitendinosus*) Beef (*M.Longissimus lumborum*) Beef (*M.Longissimus lumborum & M.semimembranosus*)	Electric field strength: 1.4 kV/cm Frequency: 50 Hz Pulse width: 20 µs Specific energy: 250 kJ/kg Electric field strength: 10 kV/cm Frequency: 90 Hz Pulse width: 20 µs Electric field strength: 5, 10 kV/cm Frequency: 20, 50, 90 Hz	Meat quality traits Tenderization Tenderization	PEF conditions and sample pre-treatment should be considered when determining the effect of PEF on meat tenderization. PEF treatment also affects the oxidative stability of frozen-thawed meat and would enhance lipid oxidation. PEF caused neither significant inactivation nor favorable conditions for microbial proliferation post-processing. No significant effect was found on total water loss, shear force, meat colour and lipid stability by PEF. A larger increase in proteolysis was observed in low-pH (5.5–5.8) samples which were reflected in shear force measurements. Beef *Longissimus lumborum* was found to get tougher with increasing treatment frequency whereas beef semimembranosus muscle was found to have up to 21.6% reduction in the shear force. Post-mortem proteolysis showed an increase in beef Longissimus lumborum treated with low-intensity PEF treatment (20 Hz).	Purge loss, Cooking loss, Shear force, Electron microscopy analysis, TBARS, Fatty acid analysis, Volatile profile Western blotting, Shear force, Cooking loss, Purge loss, TBARS, Colour, Myofibrillar protein Profile Western blotting, Shear force, Cooking loss, Purge loss, Colour, Myofibrillar protein Profile	Faridnia et al (2015) Suwandy, Carne, van de Ven, Bekhit, & Hopkins (2015c) (Suwandy et al., 2015b)

Appendix III. Application of TDS on meat and meat products

Food category	Products	Number of Panellists	Another method	TDS data analysis	References
Liquid	Hot beverages	12	TI	TDS score/MFA	Le Révérend, Hidrio, Fernandes, & Aubry (2008)
	Liquid dairy products	16	TI	TDS curve	Pineau et al (2009)
	Dealcoholized red wines	16	SP	TDS curve/CVA	Meillon, Urbano, & Schlich (2009)
	Red wines	8	-	TDS curve	Meillon et al (2010)
	Water	16	SP	TDS curve/CVA	Teillet, Schlich, Urbano, Cordelle, & Guichard (2010)
	Flavoured vodka	10	-	TDS curve	Déléris et al (2011)
	White wines	18	QDA/TI	TDS curve	Sokolowsky & Fischer (2012)
	Blackcurrant squashes	11	QDA	TDS curve/PCA	Ng et al (2012)
	Espresso coffee	16	HS/NS	TDS curve	Barron et al (2012)
	Coffee	13	-	TDS curve	Dinnella, Masi, Naes, & Monteleone (2013)
	Beer	12	TI/DP	TDS curve	Vázquez-Araújo, Parker, & Woods (2013)
	White wines	17	TI/DP	TDS curve	Sokolowsky, Rosenberger, & Fischer (2015)
	Coffee	10	HS	TDS curve	Evangelista et al (2014)
	Sweeteners	6	TI	TDS curve	Di Monaco, Miele, Volpe, Picone, & Cavella (2014)
	Sweeteners	12	-	TDS curve	Zorn, Alcaire, Vidal, Giménez, & Ares (2014)
	Espresso coffee	18	PTR-ToF-MS/HS	TDS curve	Charles et al (2015)
	Aqueous solution	10	-	TDS curve	Feltrin, De Souza, Saraiva, Nunes, & Pinheiro (2015)

Food category	Products	Number of Panellists	Another method	TDS data analysis	References
Food combination	EVOO with vegetables	13	SP	TDS curve	Dinnella, Masi, Zoboli, & Monteleone (2012)
	Salmon-sauce	9	QDA	TDS curve	Paulsen, Næs, Ueland, Rukke, & Hersleth (2013)
	Cheese on Wine	31	-	TDS curve/CVA	Galmarini, Loiseau, Visalli, & Schlich (2016)
Semi-solid	Gels	12	SP	TDS curve/PCA	Labbe, Schlich, Pineau, Gilbert, & Martin (2009)
	Cheese	16	-	TDS curve	De Loubens et al (2011)
	Yogurt	10	QDA	TDS curve/PCA	Bruzzone, Ares, & Giménez (2013)
	Yogurt	16	-	TDS curve/PCA	Bouteille et al (2013)
	Ice cream	14	-	TDS curve	Varela, Pintor, & Fiszman (2014)
	Mozzarella cheese	30	-	TDS curve	Rodrigues, Gonçalves, Pereira, Carneiro, & Pinheiro (2014)
	Cheese	7	-	TDS curve	Saint-Eve, Panouillé, Capitaine, Déléris, & Souchon (2015)
	Fruit gels	14	-	TDS curve/MFA	Agudelo, Varela, & Fiszman (2015)
	Food gels	10	QDA/PP	TDS curve/ TDS trajectory	Devezeaux de Lavergne, Derks, Ketel, de Wijk, & Stieger (2015)
	Flavoured fresh cheese	11	-	Temporal liking /CATA	Meyners (2016)
	Minas cheese	30	-	TDS curve/PARAFAC	Bemfeito, Rodrigues, Silva, & Abreu (2016)

Food category	Products	Number of Panellists	Another method	TDS data analysis	References
Solid	Wheat flakes	25	-	TDS curve/PCA	Lenfant, Loret, Pineau, Hartmann, & Martin (2009)
	Fish sticks	9	KASP	TDS curve/CVA	Albert, Salvador, Schlich, & Fiszman (2012)
	Biscuits	13	-	TDS curve/CVA	Laguna, Varela, Salvador, & Fiszman (2013)
	Bread	12	-	TDS curve/PCA	Panouillé, Saint-Eve, Déléris, Le Bleis, & Souchon (2014)
	Sausages	12	-	TDS curve/PCA	Paulsen, Nys, Kvarberg, & Hersleth (2014)
	Nuts	40	-	TDS curve	Hutchings, Foster, Grigor, Bronlund, & Morgenstern (2014)
	Sausages	23	-	TDS curve	Devezeaux de Lavergne et al (2015)
	Polenta sticks	13	-	TDS curve	Di Monaco, Miele, Volpe, Masi, & Cavella (2016)
	Cocoa	11	QDA/HS	TDS curve	Menezes et al (2016)
	Chocolate	10	HS	TDS curve	Batista, Ramos, Dias, Pinheiro, & Schwan (2016)
	Chocolate bars	10	-	TDS curve/PARAFAC	Jéssica Ferreira Rodrigues, Condino, Pinheiro, & Nunes (2016)
	Dry-cured ham	11	TI	TDS curve/PCA	Lorido, Hort, Estévez, & Ventanas (2016)
	Dry-sausages	9	KASP	TDS curve/PCA	Braghieri et al (2016)
	Potato crisps	18	-	TDS curve	Hutchings, Horner, Dible, Grigor, & O'Riordan (2016)
	Oral nutritional supplements	65	TDL	TDS curve/CVA	Thomas, van der Stelt, Prokop, Lawlor, & Schlich (2016)

an updated from Di Monaco, Su, Masi, & Cavell (2014), and using major databases (i.e., Web of Knowledge, SCOPUS) was conducted.b TI: Time Intensity; SP: Sensory Profiling; QDA: Quantitative Descriptive Analysis; HS: Headspace; NS: Nose-space; DP: Drinking Profile; KASP: Key Attribute Sensory Profiling; PP: progressive profiling; TDL: Temporal dominance of liking. c PCA: Principal component analysis; CATA: check all that apply; CVA: Canonical variate analysis; PARAFAC: Parallel factor analysis