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Power ultrasound in meat processing

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Abstract

Ultrasound has a wide range of applications in various agricultural sectors. In food processing, it is considered to be an emerging technology with the potential to speed up processes without damaging the quality of foodstuffs. Here we review the reports on the applications of ultrasound specifically with a view to its use in meat processing. Emphasis is placed on the effects on quality and technological properties such as texture, water retention, color, curing, marinating, cooking yield, freezing, thawing and microbial inhibition. After the literature review it is concluded that ultrasound is a useful tool for the meat industry as it helps in tenderisation, accelerates maturation and mass transfer, reduces cooking energy, increases shelf life of meat without affecting other quality properties, improves functional properties of emulsified products, eases mould cleaning and improves the sterilization of equipment surfaces.

Keywords: ultrasound, high power ultrasound, emerging technologies, meat quality, mass transfer, meat processing

1. Introduction

Ultrasound is an innovative technology that has applications in both the analysis and the modification of foodstuffs and is defined as being sound waves higher than those that can be detected by the human ear (20 kHz). When sound travels through a medium, it generates waves of compression and rarefaction of the particles in the medium (Povey & Mason, 1998) with the result being the formation of cavities and/or bubbles. These cavities grow with subsequent cycles of ultrasound and eventually become unstable and collapse releasing high temperatures and pressures. If this collapse is within a biological material ultrasound can affect these biological materials and tissues on micro and a macro scale. In the case of food processing, the effects are in general positive in that they can be applied to promote increased food quality and safety. The ranges of sound used are divided into high-frequency, low-intensity ultrasound (> 1 MHz, <1 Wcm^{-2}) and low-frequency, high-intensity ultrasound (20-100 kHz with 10-1000 Wcm^{-2}), also known as power ultrasound. Both types are useful in food technology. The former is non-destructive and is used for analysis or characterization of compounds while the latter can be used to modify cell structures and in a number of other processes such as foam inhibition, emulsification, inhibition or activation of enzymes and crystallization (Mason, Paniwnyk, & Lorimer, 1996; Mason et al., 2011). In meat processing, power ultrasound can modify cell membranes which can help in curing, marinating, drying and tenderising the tissue. However, these processes need to be developed further before they can be implemented at a full industrial level. The aim of this paper is to review the effects of power ultrasound on the technological properties and quality of meat.

2. Power ultrasound in meat processing

In recent years several studies have reported the effects of power ultrasound on fresh and processed meat. The resulting changes in the physicochemical characteristics, cooking, processed, brining, microbial growth, freezing, cooking and cutting of meat are summarized in Table 1.

2.1. Physicochemical characteristics

Meat quality depends on aroma, taste, appearance, texture and juiciness. Consumer behavior indicates that texture is the most important palatability factor in determining the quality of meat (Smith, Cannon, Novakofski, McKeith, Jr. & O'Brien, 1991). Texture is dependent upon factors such as the tenderness of the meat, its WHC (juiciness) and also the degree of maturation.

2.1.1 Tenderness

Traditional tenderising methods used to make poor-quality meat more palatable include mechanical, enzymatic and chemical approaches. In one of the first publications in this area research on meat sterilization using heat and ultrasound found tenderising to be a beneficial side effect of this sterilization process (Pagan, Mañas, Alvarez, & Condon, 1999) however the authors did not report the intensity and frequency of the ultrasound applied. Technically, ultrasound can act in two ways in the meat tissue: by breaking the integrity of the muscle cells and by promoting enzymatic reactions (Boistier-Marquis, Lagsir-Oulahal & Callard, 1999). While some authors (Jayasooriya, Bhandari, Torley, & D' Arey, 2004) assert that prolonged exposure to high-intensity ultrasonic waves causes a significant tenderising of the meat, others have failed to confirm this effect (Lyng, Allen, & McKenna, 1997; Lyng, Allen, & McKenna, 1998a; Lyng, Allen, & McKenna, 1998b). One study showed that sonication of beef muscle with an intensity of 2 Wcm^{-2} for 2 h at a frequency of 40 kHz damages the perimysium resulting in improved texture (Roberts, 1991). To observe changes in maturation, Pohlman, Dikeman, & Zayas (1997a) applied ultrasound (20 kHz, 22 Wcm^{-2}) for 0.5 or 10 min to shear pectoral muscles that had been vacuum-packed and ripened for 1, 6 or 10 d. The sonicated muscles showed reduced hardness with no effect of sonication time or storage of packed meat on weight loss, hardness or sensory characteristics. Non-packaged pectoral muscles that were treated ultrasonically had less weight loss than muscles processed by other methods.

A more recent report by Chang, Xu, Zhou, Li, & Huang (2012) indicated that applying power ultrasound (40 kHz, 1500 W) to *semitendinosus* beef muscle for 10, 20, 30, 40, 50, and 60 min had no significant effect on color but decreased the muscle fiber diameter with no effect on the content of heat-insoluble collagen, but with effects on the thermal stability and properties of collagen as well as the texture of meat. Kiwi protease enzyme (actinidin) participates in tenderising meat during marination, but if ultrasound (1 MHz, 150 W and 25 kHz, 500 W) is applied after injection of actinidin and meat is stored for 2 days, the marinating can be more uniform and effective (Jørgensen, Christensen, & Ertbjerg, 2008) The combination of actinidin with ultrasound resulted in a further reduction of the toughness of the meat and the results suggest that the treatments weakened both the myofibrillar and the connective tissue components of the meat.

Another study showing that ultrasound can improve tenderness and the technological properties of meat was conducted by Jayasooriya, Torley, D' Arcy, & Bhandari (2007). These authors sonicated (24 kHz, 12 Wcm^{-2}) bovine muscles for a maximum of 4 min and subsequently stored them. Sonication resulted in increases in tenderness and pH without significant interaction between ultrasound and maturation time. Ultrasound treatment did not affect the color or drip loss, but cooking losses and total losses decreased. The hypothesis that ultrasound causes mechanical disruption and muscle tenderising has also been confirmed in poultry. In a study of hen breast muscles that were treated with ultrasound (24 KHz for 15 s at 12 Wcm^{-2}) stored at 4 ℃ for 0, 1, 3, or 7 d, the shear force was reduced in the sonicated samples (Xiong, Zhang, Zhang and Wu, 2012) with no change in cooking loss. The results suggest that both ultrasound and endogenous proteases such as the calpain system and cathepsins contributed to muscle degradation.

2.1.2 Water holding capacity

It has also been shown that ultrasound facilitates release of the myofibrillar proteins, which are responsible for binding properties of the meat such as the water holding capacity (WHC), tenderness and cohesion of meat products (McClements, 1995). WHC changes depend on the *post mortem* changes in myofibrillar structure and therefore, the tenderness of the meat is related to the differences in the distribution of water during the conversion of muscle to meat (Lawrie & Ledward, 2006). Texture of meat is dependent on the WHC of meat, which is itself influenced by heating. When sonicated meat was cooked at 50 ℃, it was softer than the control. However, when cooked at 70 ℃, it was tougher than unsonicated meat as it appears that ultrasound treatment decreases water loss in refrigeration, thawing and cooking between 50-70 ℃. Therefore, Dolatowski, Stasiak, & Latoch (2000) suggest that ultrasound treatment could help change the textural properties of meat and increase the WHC after thawing and thermal processing without effect on the pH of the treated meat.

2.1.3 Maturation

The hypothesis that the application of ultrasound treatment may cause an acceleration of the maturation process has been repeatedly confirmed. Dolatowski & Stadnik (2007) and Stadnik & Dolatowski (2011) sonicated calf *semimembranosus* muscle at 24 h *post mortem* for 2 min and stored it for 24, 48, 72 or 96 h at 2 ℃. No change s in pH or color were observed, but there was an increase in the WHC in the sonicated samples, similar to that of the matured meat. Thus, the authors suggested that treatment with ultrasound accelerated *rigor mortis* since they also observed fragmentation in the structures of cellular proteins (Stadnik, Dolatowski, & Baranowska, 2008).

In contrast, other studies have not confirmed the maturation effect of ultrasound on beef (Lyng, Allen, & McKenna, 1997; Lyng, Allen, & McKenna, 1998a) or lamb (Lyng, Allen, & McKenna, 1998b) when using intensities from 0.29 to 62 Wcm^{-2} for periods of 15 s and post mortem maduration times from 1 to 14 days. These authors found no changes in the hardness of the meat, chewing force, sensory characteristics, solubility of collagen or myofibrillar proteolysis. Comparisons between works can not be made because equipment differences meant that intensities and frequencies of exposure were not similar between experiments. In other studies. Got et al. (1999) treated *semimembranosus* muscle with ultrasound (2.6 MHz, 10 Wcm^{-2}, 2 x 15 s) *pre rigor* (day 0, pH 6.2) or *post rigor* (day 1, pH 5.4) and found an effect only in the *pre rigor* condition. This treatment group displayed greater elongation of the sarcomere with ultrastructural alterations in the region of the Z line and an increase in cytosolic calcium.

In assessing the influence of ultrasound treatment on the oxidative stability of beef (*semimembranosus*) during maturation, Stadnik & Dolatowski (2008) sonicated packed meat with frequency of 45 kHz in an ultrasound bath. The low intensity ultrasonic field (2 Wcm^{-2}) was applied perpendicularly to muscle fibers for 120 s. Meat samples were then stored at 4℃ for a total of 4 days. This study demonstrated that sonication in conjunction with refrigerated storage can be an effective method to improve the technological properties of beef without compromising its oxidative stability.

In spite of the difficulties in comparing different experiments due to differences in frequency/intensity/time combinations of the ultrasound applied to meat it is evident that the majority of papers claim favourable effects of ultrasound on meat texture. From this it can be concluded that power ultrasound has a significant effect on the texture and maturation of meat from various species by weakening myofibrillar and connective tissues and reducing cooking losses without affecting other quality parameters.

2.2 Cooking and processing

Ultrasound has the ability to improve the characteristics associated with heat transfer, which is a key requirement in the cooking of meat (Hausgerate, 1978). There is a patent describing a special container for cooking meat in which the ultrasound is applied to hot oil for better, more uniform frying with a concomitant reduction in energy consumption (Park & Roh, 2001). One study (Pohlman, Dikeman, Zayas, & Unruh, 1997b) investigated the effects of ultrasound on either ultrasonically (20 kHz, 1000 W) or conventionally cooked *longissimus thoracic* and pectoral beef muscles. Muscles were cooked to a final internal temperature of 62 or 70 ℃ and matured for 14 d at 2 ℃. Cooking in the presence of ultrasound resulted in faster cooking speeds, higher water retention and lower cooking losses. In addition, the cooked meat was also superior in myofibrillar tenderness, had fibers of larger diameter and a greater amount of myofibrillar rupture than the meat cooked solely by convection. This study identifies ultrasound as a method for cooking meat fast that is also more efficient in terms of energy consumption and can improve the texture of meat compared to the convection cooking method. The lower water loss in sonicated meat can be explained by the fact that the application of high intensity ultrasound increases the WHC of meat (McClements, 1995). An additional advantage is that muscles cooked with ultrasound have two to five times less cooking losses that meat cooked by boiling and convection due to a more efficient heat transfer mechanism. This suggests that ultrasound is helpful in preparing precooked meats for use in restaurants or in the prepared-dishes industry (Chemat, Zill-e-Huma, & Khan, 2011).

Ultrasound has been used to improve the production of processed meat. In this process the meat pieces are held together by a gel of myofibrillar proteins released during processing (McClements, 1995). The mixing of the pieces of meat and the addition of salt cause the release of proteins, thereby forming a sticky exudate that binds the pieces of meat together when they are pressed and molded. Vimini, Kemp, & Fox (1983) examined the effect of ultrasound on the extraction of proteins using ultrasound to disrupt the myofibres of the meat. They found that samples that received both ultrasonic irradiation and tumbling in salt were superior in binding strength, water-holding capacity, product colour, and cooking yields to specimens that had only one treatment. Products that received only sonication were similar in exudate yield, cooking yield, and water-holding capacity to products produced by the conventional salt treatment, but had much lower binding strengths because salt is necessary to gel the protein. Similar observations were made on cured ham rolls by Reynolds, Anderson, Schmidt, Theno, & Siegel (1978). Applying ultrasound to salted chicken breast increases the water retention capacity, tenderness and cohesion, extraction of myofibrillar proteins and therefore the textural properties of the reformed meat product. In order to explore new methods of reducing the content of saturated fatty acids in meat products, vegetable pre-emulsified lipids were employed to replace animal fat using ultrasound (Zhao et al., 2014). Gels were prepared with 3% breast protein and 27.5% pre-emulsified soy oil with 0.5% sodium caseinate. Rheological tests showed that the samples treated with pulses of ultrasound (20 kHz, 450 W for 0, 3, 6, 9 and 12 min) form a gel that is more viscoelastic than the control and the binding capacity of water, fat profile and the texture are also improved. The gels exhibited fine microstructure and homogeneous networks when the ultrasound time was 6 min. These findings demonstrate that ultrasound treatment has the potential for producing emulsified meat products with excellent functional properties and improved the fatty acid composition at high yields (Zhao et al., 2014).

2.3 Brining

Brining of meats is an old process used for food preservation, it consists of immersing a cut of meat in a solution of salt (brine), this process enhances shelf-life, flavor, juiciness and tenderness of the products. During brining meat is immersed in saturated salt solutions and two main mass transfer processes take place. The water migrates from meat to brine and the solutes migrate from brine to meat (Carcel, Benedito, Bon, & Mulet, 2007). The diffusion of NaCl into the matrix of the meat is normally slow but can be improved by injection, however this process produces lower-quality cured products. It has been observed that the permeability of the muscle tissue increases with ultrasound and this can be used to estimate the effect of ultrasound in the brining of meat (Leal-Ramos, Alarcon-Rojo, Mason, Paniwnyk, & Alarjah, 2010). Carcel, Benedito, Mulet, & Riera (2003) investigated the influence of ultrasound intensity on mass transfer. Pork loin slices were soaked in a saturated solution of NaCl at 2^{o}C for 45 minutes. Different types of agitation of the solution and different levels of ultrasound intensity were applied during brining. The water and NaCl content of samples after such treatments showed a significant influence of ultrasound intensity on the mass transfer. Above a threshold ultrasonic intensity, NaCl and water content were higher in sonicated than non-sonicated samples. In another paper Carcel, Benedito, Bon, & Mulet (2007) reported similar results at higher experimental temperatures. They showed that when slices of pork tenderloin were soaked in saturated NaCl solution at 21 ℃ for 45 m in and sonicated at 20.9 to 75.8 Wcm^{-2} the water and NaCl content of the samples increased with the ultrasound intensity. These results demonstrated that when ultrasound was applied the rate of gain of NaCl increased compared with curing under static conditions, suggesting that ultrasound improved the transfer of both external and internal mass. These authors showed that the mass transfer was not affected until intensity thresholds were reached (39 and 51 Wcm^{-2}) but that above these, the higher the level of ultrasound intensity that was applied, the greater was the effect of ultrasound on mass transport. This effect was also observed with intensity levels as low as 1.3 Wcm^{-2} at a frequency of 290 kHz (Mulet, Carcel, Sanjuan, & Bon, 2003) when salting slices of pork tenderloin with and without ultrasound. The relation of ultrasound intensity and salt diffusion in meat has continued to be reported. Siro et al. (2009) applied three brining treatments (static brining, vacuum tumbling, or ultrasonic brining at low-frequency (20 kHz) and low-intensity (2–4 W cm^{-2}) to pork loins. They observed a significant improvement in salt diffusion compared to samples in brine under static conditions and the diffusion coefficient exponentially increased with increased ultrasonic intensity.

The potential application of ultrasound to industrial ham production was demonstrated by McDonnell, Lyng, Arimi, & Allen (2013). In a pilot study, these authors applied ultrasonic treatments at intensities of 40, 56 or 72 Wcm^{-2} for 2, 4 or 6 h. In all of these the desired level of NaCl (2.25%) was reached within 2 h while the control required 4 h. Applications of 40 and 56 Wcm^{-2} caused a greater loss of meat weight than the control, possibly due to loss of protein. Sonication showed no effect on cooking loss, free moisture or texture profile. Sensory analysis revealed an increase in cooked ham flavor with increasing ultrasound power. Ozuna et al. (2013) confirmed that the effective diffusivity of NaCl and moisture improved with the application of ultrasound. In addition NaCl content, final moisture content and use of ultrasound produced changes in the texture of the meat which were demonstrated through microstructural observations. Recently, McDonnell, Lyng, Morin, & Allen (2014) studied the effect of treatment with power ultrasound (4, 2, 11 or 19 Wcm^{-2} for 10, 25 or 40 min) on the curing of pork and the results indicated that salting with ultrasound could be a surface phenomenon that can accelerate mass transfer and also extract proteins, but it can also denature myosin when high power ultrasound is applied. The benefits of ultrasound on mass transfer are very convincing and industrial implementation could be very close.

2.4 Microbial growth

Alternative methods of food processing that have an almost zero influence on the quality of food have become more important due to increased consumer demand for minimally-processed foods. Ultrasound processing is an alternative technology that has shown promise in this field. With ultrasound technology, high pressure, shear, and a temperature gradient are generated by high power ultrasound (20 to 100 kHz), which can destroy cell membranes and DNA, thus leading to cell death (Chen et al., 2012). A relatively new concept in antimicrobial treatment has been proposed involving the combined effect of pressure and ultrasound (manosonication), ultrasound and heat (thermosonication) or the combination of ultrasound, heat and pressure (manothermosonication) (Pagan, Mañas, Alvarez, & Condon, 1999). These are probably the best methods to inactivate microbes as they are more energy efficient and effective at inhibiting a range of microorganisms. The effectiveness of ultrasound requires prolonged exposure to high temperatures which can cause deterioration of the functional properties, sensory characteristics and nutritional value of food (Piyasena, Mohareb, & McKellar, 2003). However in combination with heat, ultrasound can accelerate the rate of sterilization of food thus decreasing the duration and intensity of the heat treatment and the resulting damage. Morild, Christiansen, Anders, Nonboe, & Aabo (2011) evaluated the inactivation of pathogens by the application of pressurized steam simultaneously combined with high-power ultrasound on the surface of pig skin and meat. The inactivation of *Salmonella typhimurium*, *Salmonella derby*, *Salmonella infantis*, *Yersinia enterocolitica*, and a non-pathogenic *Escherichia coli* were studied in inoculated samples treated with 30-40 kHz ultrasound for 0.5 – 4.0 s. Total counts of viable bacteria were reduced 1.1 log CFU cm^{-2} after treatment for 1 s and 3.3 log CFU cm^{-2} after treatment for 4 s. The reduction of microorganism levels in the pig skin was significantly greater than the reduction found in the meat. In contrast with these results Smith, Cannon, Novakofski, McKeith, & O'Brien Jr. (2011) reported no effect on *Salmonella* or *E. coli* in chicken meat marinated with the help of ultrasound. This suggests that in some cases ultrasound alone might not be fully effective in inhibiting bacterial growth. The low power of the ultrasonic bath used and non- antimicrobial marinade solution were likely responsible for the findings. Kordowska-Wiater & Stasiak (2011) investigated the removal of Gram-negative bacteria (*Salmonella anatum*, *Escherichia coli*, *Proteus sp*. and *Pseudomonas fluorescens*) from the surface of chicken skin after treatment with ultrasound (40 kHz and 2.5 Wcm^{-2} for 3 or 6 min) in water and in aqueous 1% lactic acid. Sonication in water alone or in lactic acid for 3 min resulted in a reduction of the number of microorganisms on the skin surface by 1.0 CFU cm^{-2}, but longer treatment (6 min) resulted in a reduction of more than 1.0 CFU cm^{-2} in the water samples and 1.5 log CFU cm^{-2} in the lactic acid samples. Ultrasound treatment in combination with lactic acid may be a suitable method for decontamination of the skin of poultry. Herceg et al. (2013) studied the effect of high-intensity ultrasound on the inactivation of suspensions containing *Escherichia coli, Staphylococcus aureus*, *Salmonella sp.*, *Listeria monocytogenes* and *Bacillus cereus* treated with an ultrasound probe of 12.7 mm at 20 kHz and amplitudes of 60, 90 and 120 mm for 3, 6 and 9 min at 20, 40 and 60 ℃. Increasing any of these three parameters improved the inactivation of bacteria in pure cultures. The results also showed increased inactivation after longer periods of treatment, especially in combination with high temperature and amplitude. Recent reports show that steam treatment and ultrasound applied to chicken carcasses in a processing line can significantly reduce the number of *Campylobacter* on contaminated birds. The total viable count was reduced by approximately three logs by applying steam and ultrasound immediately after slaughter (Hanieh, Niels, Nonboe, Corry, & Purnell, 2014).

2.5 Freezing and thawing

Ultrasound aids crystallization by controlling nucleation and crystal growth in frozen foods (Luque de Castro & Priego-Capote, 2007). It also affects texture and the release of thawed cell liquid (Zheng & Sun, 2006), which are of major importance for consumer acceptance of meat products, fruits and vegetables, as well as for the conservation of both nutrient and bioactive ingredients.

Transformation of sound energy to heat can be utilized in accelerated thawing. This process is greatest in the frozen phase and increases as the sub-zero temperature rises. In contrast to microwaves, ultrasound heats up the ice at a greater rate than the thawed water (Dolatowski, Stasiak, & Latoch, 2000). Acoustic thawing is an innovative technology in the food industry if the appropriate frequencies and sound power are chosen. However, Miles, Morley, & Rendell (1999) observed that overheating near the surface was a problem at high intensities both at high and low frequencies. Using frequencies and intensities around 500 kHz and 0.5 W cm^{-2} respectively, surface heating was minimized, and beef, pork and cod samples were thawed to a depth of 7.6 cm within about 2.5 h. Acoustic thawing shortens the defrost time, thus reducing drip loss and improving product quality (Li & Sun, 2002). Recently, a study was conducted which compared the physical, chemical, *microbiological and technological features in the packing of pork longissimus thoracis or lumborum* thawed at low intensities of ultrasound with a control of immersion in water. Thawing was performed at a constant temperature and at a frequency of 25 kHz and with ultrasound intensities of 0.2 Wcm^{-2} or 0.4 Wcm^{-2}. There were no significant differences in the chemical, microbiological or textural properties between the meats thawed by ultrasound or by water (Gambuteanu & Alexe, 2013).

2.6 Cleaning and sterilisation processes

Ultrasonic cleaning is an area with a very large amount of background material particularly for the sterilisation of hard surfaces e.g. food trays, chicken shackles (Quartly-Watson, 1998). Generally, the industrial cooking of foods leads to adhesion of the products to the cooking vessel. To remove the cooked product from the mould is difficult, however in industrial processing of moulded food products, the thin layer of silicone or Teflon (polyterafluorethylene) on the moulds surface is used but this has to be applied periodically because the shelf life of this layer is relatively short. Such operations are expensive and not always totally successful. At present, to solve this problem mechanical methods such as vibrations induced by knocking the container are used to remove the products. An alternative solution is to release food products by subjecting the mould to a source of ultrasound (Scotto, 1988). The device for demoulding industrial food products couples the mould and the ultrasonic source in order to enhance removal using the high frequency relative movement between the contact surfaces of the mould and of the product contained in it. This technique does not normally require any special surface coatings. A similar property of ultrasound is required to aid extrusion i.e. the ability to release material from a surface thus reducing drag. The energy input is provided by ultrasonic excitation of the metal tubes through which the food is extruded. The ultrasonic source gives the tubes a radial vibration improving the flow behaviour of sticky or highly viscous materials through the tube by lowering drag resistance and it can also modify product structures (Knorr, Zenker Heinz, & Lee 2004; Akbari Mousavi, Feizi, & Madoliat, 2007).

2.7 Cutting of frozen meat and processed meat

Ultrasonic cutting has been available to industry since the early 1950's specifically for accurate profile cutting of brittle materials such as ceramics and glass. Ultrasonic cutting uses a knife type blade attached through a shaft to an ultrasonic source. Essentially the shaft with its blade behaves as an ultrasonic horn driven normally at 20 kHz and with a generator similar to that of a welder operating at around 2 kW. The cutting action is a combination of the pressure applied to the sharp cutting edge surface and the mechanical longitudinal vibration of the blade. Typically the tip movement is in the range 50 to 100 microns peak to peak (Rawson, 1988). Several advantages arise from this technology: the ultrasonic vibration of 20kHz minimises the stress, reduces significantly the overall force required to break the bonds and reduces the co-efficient of friction to a very low level, enabling the blade to slide more easily through the bulk material.

The cutting tool itself can be of many shapes and each shape can be considered to be an acoustic horn, part of the whole ultrasonic resonating device. Cutting with the superimposition of ultrasonic vibration is a direct competitor of technologies such as high velocity water jet cutting and conventional techniques like saws, knives etc. The energy requirements for ultrasonic cutting have been investigated (Schneider, Zahn & Rohm, 2008). The ultrasonic cutting characteristics depend upon the food type and condition e.g. frozen or thawed (Brown, James, & Purnell, 2005). The most widespread application of ultrasound is the cutting of fragile foodstuffs. Indeed it is well adapted to food which cannot tolerate great deformations under the effect of a blade, or to products that are difficult to slice by the tools traditionally used like rotary blades or knives with teeth. Another characteristic of this technique lies in hygiene improvement since the vibration prevents the adherence of the product on the blade and thus reduces the development of microorganisms on the surface i.e. ultrasonic vibrations provide “auto-cleaning” of the blade. The accuracy and repetitively of the cut produces a reduction in losses relative to the cutting and a better standardisation of the weight and dimensions of portions.

2.8 Power ultrasound negative effects in meat processing

The impact of power ultrasound in meat processing has been rarely associated with having any negative or adverse effects in meat. However some effects include adverse changes in water binding capacity (Siró et al., 2009), colour stability (Stadnik, 2009), juiciness, sensory properties and yield of meat (Barbieri & Rivaldi, 2008). It is believed that these changes are caused by physical and chemical alterations in meat proteins (McDonnell, Allen, Morin & Lying, 2014) but this has yet to be confirmed. Acoustic energy can be absorbed, giving rise to elevated temperatures due to cavitation resulting in thermal damage of food (Reza Kasaai, 2013) and some studies have also demonstrated that thermosonication can cause extensive physical damage to the outer cell membrane (Mañas & Pagán, 2005).

Sonication is also known to depolymerize macromolecules even without the presence of bubble collapse due to shear stresses within the liquid medium (Feng, Yang, & Hielscher, 2008) with chain fragmentation increasing with an increase in ultrasonic power (Reza Kasaai, 2013). The ultrasound stability of individual proteins varies between different enzymes due to the different amino acid composition and the conformational structure of the enzyme and also whether they are bound (e.g., membrane-bound proteins) or free (e.g., cytoplasmic proteins) (Ercan & Soysal, 2013). Cysteine, and methionine are the amino acids thought to be most susceptible to oxidative changes due to the susceptibility of their sulfur groups to radical attack. Changes induced by high intensity ultrasound depend on the nature of the protein and its degree of denaturation and aggregation (Arzeni et al., 2012). High intensity ultrasound induces modifications on food protein functionalities such as gelation, viscosity and solubility and those changes are believed to be closely related to molecular modifications, mainly hydrophobicity increase and particle size variation. Protein oxidation in food systems could also result in protein fragmentation or protein-protein cross-linkages Oxidative modifications of proteins can change their physical and chemical properties, including conformation, structure, solubility, susceptibility to proteolysis, and enzyme activities (Zhang, Xiao, & Ahn, 2013). These modifications could also determine the fresh meat quality and influence the processing properties of meat products.

Introduction of radicals during food processing, as a result of ultrasonically induced homologous fission of water molecules, can aid in food oxidation (Reza Kasaai, 2013). The use of ultrasound by industry should therefore consider the introduction of radical quenchers as a method of radial control in order to prevent unwanted oxidation reactions (Ashokkumar et al., 2008).

The results obtained from studies using ultrasound in food systems are difficult to compare due to different food macromolecules and the role they have in the properties of each food. The research to date has not been sufficient to clearly establish the possible negative effects ultrasound could have on meat quality. Although it is known that ultrasound exerts changes in food molecules and some changes have been observed in the treated meat, there is a lack of evidence of the relationship of ultrasound and the endogenous meat components related to functional properties and eating quality of meat.

3. Conclusions

High-power ultrasound has been shown to effectively increase the tenderness of meat by causing disruption of the muscle integrity and modifying the structure of collagen. In addition, it can improve the technological properties of meat without compromising other quality parameters. However, more research is needed before proposing a recommendation to the food industry on the potential of ultrasound as a meat tenderizer. It has also been demonstrated that ultrasound can accelerate conventional cooking and provide an innovative, rapid meat cooking method that is energy efficient and can improve texture attributes of the meat.

In addition ultrasound can reduce brining time without affecting meat quality and the diffusion of salt increases with the intensity of ultrasound without significant changes in other characteristics of the meat. Likewise, the treatment of poultry skin with ultrasound in combination with lactic acid was shown to be a suitable method for the inactivation of microorganisms. Furthermore, the total count of microorganisms is reduced by applying steam and ultrasound immediately after slaughter. It should also be noted that acoustic thawing decreases both the defrosting time as well as the drip loss thus leading to much reduced defrost times without loss of meat quality.

Also ultrasound enhances removal of moulded and extruded products and ensures the automatic cleaning of the mould or extrusion metal tubes. Successful cutting of frozen or processed meat can be done using ultrasound, enhancing the quality of the process and reducing the product losses.

Finally, it is worth mentioning the need for a more thorough investigation in the above fields of meat processing. Some ultrasonic innovations are already close to being used on a large scale whereas the potential for many other applications exists in other areas.

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Table 1. Summary of the effects of ultrasound in meat processing

Sample	*Application (Intensity/Freq/time)*	*Effect of ultrasound*	*Authors*
Sirloin	2 Wcm^{-2}, 40 kHz, 2 h.	Damage perimysal connective tissue. Improve eating texture.	Roberts, 1991
Beef (*pectoralis*)	22 Wcm^{-2}, 20 kHz, 0.5 or 10 min	Hardness reduction. Less intense red color and more orange color with storage and ultrasound. Reduced cooking losses.	Pohlman, Dikeman, & Zayas, 1997a
Beef (*longissimus thoracis and lumborum, semimembranosus and biceps femoris*)	.29, .39 and .62 Wcm^{-2}, 20 kHz, 15 s	No effect on tenderness and aging of the meat.	Lyng, Allen, & Mckenna, 1997
Beef (*longissimus thoracis and lumborum, and semimembranosus*)	62 Wcm^{-2}, 20 kHz, 15 s	No effect on mastication force, sensory characteristics, solubility of collagen or myofibrillar proteolysis.	Lyng, Allen, & Mckenna, 1998a
Lamb (*longissimus thoracis and lumborum*) matured for 1, 3 and 14 d. *Pre- and post-rigor.*	62 Wcm^{-2}, 20 kHz, 15 s	No effect on bite force, collagen solubility or sensory properties.	Lyng, Allen, & Mckenna, 1998b
Semimembranosus pre- and post-rigor	10 Wcm^{-2}, 2.6 MHz, 2 x15 s	Larger sarcomeres, Z-line disruption, increased calcium. No effect on collagen. Slight *pre-rigor* effect but no effect if applied *post-rigor*.	Got et al., 1999
Beef (*semimembranosus*)	2 Wcm^{-2}, 25 kHz, 1 or 2 min	Lower loss of water after cooling, thawing and heating. No effect on pH. Higher water holding capacity.	Dolatowski, Stasiak, & Latoch, 2000
Beef (*semimembranosus*) matured for 24, 48, 72 or 96 h at 2 ℃	2 Wcm^{-2}, 45 kHz, 2 min	No effect on meat color. Increased free calcium. Changes in protein structure. Improved WHC at 4 d *post mortem*.	Dolatowski and Stadnik, 2007
Beef (*semimembranosus*) 24 h post mortem and matured for 24, 48, 72 or 96 h at 2 ℃	2 Wcm^{-2}, 45 kHz, 2 min	No effect on pH or color. Reduced hardness.	Stadnik and Dolatowski, 2011
Beef (*semimembranosus*)	45 kHz, 2Wcm^{-2}	Acceleration of aging process	Stadnik, Dolatowski &

24 h post mortem and matured for 24, 48, 72 or 96 h at 2 ℃		Fragmentation of protein structures Increase WHC	Baranowska, 2008
Beef Longissimus lumborum et thoracis and Semitendinosus aged up to 8.5 days	24 kHz, 12 Wcm^{-2} for up to 240 s	Reduced WBS force and hardness Increased pH. No interaction between ultrasound and aging. No changes in meat color and drip loss. Ultrasound reduced cook and total loss.	Jayasooriya, Torley, D' Arcy, & Bhandari, 2007
Hen breast meat 0, 1, 3, or 7 d at 4 ℃	24 kHz, 12 Wcm^{-2}, 15 s period	Reduced shear force. No change in cooking loss.	Xiong, Zhang, Zhang and Wu, 2012
Beef (*semitendinosus*)	40 kHz, 1500 W 10, 20, 30, 40, 50, and 60 min	No effect on brightness and red color. Decreased the tendency to yellow. Decreased the muscle fiber diameter. No effect on heat-insoluble collagen. Weaken collagen stability.	Chang, Xu, Zhou, Li, & Huang, 2012
Pork *biceps femoris* *24 h post mortem*	1 MHz, 150 W and 25 kHz, 500 W, 40 min plus kiwi protease (actinidin)	Ultrasound did not change in shear force. Ultrasound combined with actinidin decreased shear force more than actinidin alone.	Jørgensen, Christensen, & Ertbjerg, 2008
Raw and cooked shrimp	30 kHz, 800 W) at 0 ℃ or 50 ℃ for 0, 2, 8, 10 or 30 min	Reduced allergenicity without change in texture.	Li, Li, Lin, & Samee, 2011
Beef (*semimembranosus*) 24 h post mortem and matured for 24, 48, 72 or 96 h at 2 ℃	2 Wcm^{-2}, 45 kHz, 2 min	Slightly less stable color. No change in oxidative stability at 4 d storage.	Stadnik & Dolatowski, 2008
		Improved heat transfer during cooking More even overall frying Reduced energy consumption	Hausgerate, 1978 Park & Roh, 2001
Beef *longissimus thoracic* and deep *pectoralis* Matured 14 d at 2 ℃ Cooked at 62℃ or 70℃	20 kHz, 1000 W	Faster cooking, higher water retention, decreased cooking loss, shear force and soluble collagen. Higher sensory tenderness.	Pohlman, Dikeman, Zayas, & Unruh, 1997b
Beef meat for beef rolls	Ultrasonic irradiation	Higher cell disruption and lower cooking loss.	Vimini, Kemp, & Fox

	and tumbling in salt. No US data available.	Superior in binding strength, water-holding capacity, product colour, and cooking yields.	(1983
Pork meat for ham rolls	Ultrasonic and salt	Increased water retention capacity, tenderness and cohesion, extraction of myofibrillar proteins and textural properties.	Reynolds, Anderson, Schmidt, Theno, & Siegel, 1978
Chicken breast and soybean gels 4℃ to 8℃	20 kHz, 450W 0, 3, 6, 9 and 12 min (4 or 2 s pulses)	More viscoelastic gel Improved WFB and textural properties Homogeneous fine network microstructures	Zhao et al., 2014
Chicken breast	40 kHz, 22 Wcm^{-2} 15 or 30 min	Increased mass transfer and higher meat weight	Leal-Ramos, Alarcón-Rojo, Mason, Paniwnyk, & Alarjah, 2010
Pork loin in NaCl saturated solution	45 min, 2 ℃	Higher NaCl and water content above a threshold ultrasonic intensity.	Carcel, Benedito, Mulet & Riera, 2003
Pork loin in NaCl saturated solution	100 W and 20 kHz	Increased salt gain and water loss. Mass transfer threshold (39 y 51 Wcm^{-2}). Higher mass transfer at higher ultrasound intensity.	Carcel, Benedito, Bon, & Mulet, 2007
Pork loin	0.4 and 1.3 Wcm^{-2} 15, 30, 45, 60, 90 and 120 min	Greatert mass transfer. Higher salt content at higher power.	Mulet, Carcel, Sanjuan, & Bon, 2003
Pork *Longissimus dorsi*	2-4 Wcm^{-2}, 20kHz	Higher salt diffusion. Diffusion coefficient increases with ultrasound intensity.	Siró et al. 2009
Longissimus dorsi cerdo	40 kHz; 37.5 W/dm^3	Higher salt and water diffusion.	Ozuna, Puig, García-Pérez, Mulet, & Cárcel, 2013
Pork *Longissimus thoracis and lumborum*	0, 40, 56, 72 Wcm^{-2}, 34-40 kHz, 2, 4, 6 h	Reduction of salting time without changes in sensory attributes.	McDonnell, Lyng, Arimi, & Allen, 2013
Pork *Longissimus thoracis and lumborum*	4.2, 11 or 19 W cm^{-2}, 20 kHz, 10, 25 or 40 min	No effect on water holding capacity and structure of meat. Higher mass transfer and protein extraction. Myosin denaturation at higher intensities.	McDonnell, Lyng, Morin, & Allen, 2014
	20 to 100 kHz	Cell membranes and DNA destruction. Cell death	Chen et al., 2012

Por meat and skin surface	High-intensity ultrasound, 0.5 a 2 seg	Less skin and surface bacteria	Morild, Christiansen, Anders, Nonboe, & Aabo, 2011
Chicken breast	Ultrasonic bath, 20 min	No effect on water retention capacity, shear force and cooking loss. No changes in Salmonella and E. Coli.	Smith, Cannon, Novakofski, McKeith, & O'Brien Jr., 2011
Chicken wing surface	2.5 Wcm-2, 40 kHz, 3 or 6 min	Microorganism reduction. Higher reduction with higher time. E coli more sensible to ultrasound.	Kordowska-Wiater & Stasiak, 2011
Pure culture suspensions	20 kHz, 3, 6 and 9 min, 20, 40 and 60 ℃	Bacteria inactivation is higher at higher time and temperature.	Herceg et al. 2013
Chicken carcasses	Campylobacter and total count reduction.	Campylobacter and viable total count reduction.	Hanieh, Niels, Nonboe, Corry, & Purnell, 2014
		Controlled nucleation and crystal growth	Luque de Castro & Priego-Capote, 2007
Several foods	> 1 Wcm^{-2}, 20 a 40 kHz, >10 seg	Less tender and lower liquid loss during thawing.	Zheng y Sun, 2006
Beef, pork and fish	≤3 Wcm^{-2}, 0.22 a 3.3 MHz	Heating decreases with 500 kHz and 0.5 Wcm^{-2}. Thawing (7.6 cm deep) in 2.5 h.	Miles, Morley, & Rendell, 1999
		Improved texture and the release of thawed cell liquid	Li & Sun, 2002
Pork *Longissimus dorsi*	0.2 Wcm^{-2} y 0.4 Wcm^{-2}, 25 kHz	Less thawing time. No changes of chemical, microbiological, and textural properties of meat.	Gambuteanu y Alexe, 2013
		Improved sterilisation of hard surfaces.	Quartly-Watson, 1998
	Low-frequency vibrations	Improved demoulding.	Scotto, 1988
		Aid extrusion by improved material flowing.	Knorr, Zenker, Heinz, & Lee 2004
	20 kHz, 2 kW	Minimises the stress, reduces the force required to break the bonds and reduces the coefficient of friction in cutting.	Rawson, 1988