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Review

Review: Automation and meat quality-global challenges.☆,☆☆

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ABSTRACT

The global meat industry has seen significant changes in the methods used to harvest and process fresh meat over the past century. Increased use of automation has led to significant increases in line speed for beef, pork, sheep, poultry and fish operations. For example, currently the fastest line observed has been broilers at 13,500/h. Such developments have required in-depth understanding of the pre and post rigor processes to prevent defects. Procedures such as maturation chilling and electrical stimulation are now common in red meat and poultry processing; allowing shorter time to deboning, while harvesting high quality meat. Robots designed to cut meat are also appearing on the market, and replacing traditional manual operations. This is a challenge, because high speed equipment is not necessarily sensitive to variations in size/quality issues, and requires development of unique sensors and control systems. Also, progress in breeding and genetics is contributing to greater product uniformity and quality; helping in operating automated equipment.

Contents

1. Introduction

The changes experienced by the meat industry over the past half a century have probably dwarfed the changes that have been realised in the trade over the past two millennia. The discovery of electricity and the development of scientific knowledge (e.g., muscle biology, chemistry and physics), measuring equipment as well as accessories, such as computers and cameras, have had a major impact on the meat industry. Mechanisation and automation have increased in the world after the industrial revolution (Anonymous, 2012). The fresh meat industry has been lagging behind in some aspects, but now is starting to catch on while introducing more automation into various processes.

It is important to note that quite a few of the meat products consumed today have their roots in ancient times. Fresh cuts such as leg of lamb, and wild boar chops have been consumed for thousands of years. Processed products such as dry Salami, (believed to be developed in the hot climate area of the Mediterranean), have been made for thousands of years and are examples of how meat was preserved before the introduction of refrigeration. The name Salami is based on the word 'salt' which was used to preserve the product by reducing the water activity. Although the concept of water activity was not familiar to our ancestors, or the world of microorganisms, they learned that by adding salt and rapidly drying the product they could extend the shelf-life of the product.

An interesting way to discuss the changes experienced by the meat industry is to bring an "imaginary Roman Soldier" into a modern meat processing plant and explain to him how things work. If one starts

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with the different steps of primary processing (Table 1), it could be seen that the basic steps used two thousand years ago are mostly still used today. Bringing the animal to the abattoir is the same process; however, distances and the use of modern transportation (e.g., trucks) are quite different. This means that factors such as feed withdrawal time and animal welfare issues are getting more attention today. When the Roman Soldier is shown a computer screen used to register the animals brought into a processing plant, he might recognise the procedure of keeping inventory but he would be amazed and not understand what a touch screen, computer, electricity, and moving information wirelessly are. The latter would appear to be magic as "items" appear and disappear from thin air. It is interesting to note that the Roman Soldier would actually have all the basic equipment to slaughter, butcher and consume an animal (i.e., his sword). Another important fact to recognise is that in ancient times meat consumption mostly took place during festivals or on holydays (at least for the average person), as most animals were primarily used for work in the field.

Referring to the first basic step (Table 1) of catching/gathering the animals (e.g., placing in chicken coups or gathering beef animals) is similar to what mankind has been doing for thousands of years. Bringing the animals to a specialised abattoir is a process that was not always done; however, many cultures used to keep a certain place designated for slaughtering animals. Today with the use of highly specialised equipment and skilled labour force, dedicated processing plants have been built to service an area of a few hundred kilometres around them. Prior to that, activities such as the big cattle-drives (e.g., in North America) included moving animals by-foot, for up to a few thousand kilometres, to urban centres. This also resulted in selectively breeding animals that were very strong (capable of walking long distances), but also with lots of connective tissue. Those tough muscles would not be acceptable to the average consumer today. Therefore over the past century some efforts have been made to develop tender meat by using breeding programs. However, it should be pointed out that in the past few decades, breeding programs have been mainly used for increased productivity (growth rate, feed conversion efficiency, carcass quality). Some of the progress in meat quality also resulted from favourable genetic correlations (e.g., less connective tissue in faster growing animals, and improved management). Other procedures currently used to address tenderness include mechanical tenderisation, and chemical interventions such as injecting calcium to activate certain proteolytic enzymes.

Although this paper focuses on primary processing, it should be pointed out that steps involved in further processing have been automated to an even greater degree, mainly due to the higher uniformity of raw meat cuts arriving at the processing plant. An example of this is a fully automated batter and breading line where thousands of chicken/pork/fish nuggets can be produced every hour without human intervention. The process usually starts with a high volume former (traditionally high pressure but today also a new low pressure former), where every minute a few hundred identical nuggets/patties are produced. Another example is the co-extrusion process developed for direct semi-liquid casing application onto meat coming from the stuffer. These two examples illustrate the point of moving the operation from a batch to a continuous operation, where the introduction of innovative equipment has allowed for the replacement of manual labour, as well as increasing sanitation standards. It is important to note that where labour costs are expensive more automation and robotics are becoming a commonplace as compared to areas where labour is inexpensive, or where very complex operations are required (e.g., separating beef/pig primal cuts, de-boning of a whole chicken leg with skin on).

During the past half a century, quite a lot of work has been done by animal scientists, physiologists, meat scientists, breeders, animal welfare people, and engineers to make sure meat quality is not negatively affected by increasing line speed and shortening time to deboning. It is also important to note that large variations in procedures and techniques exist within the meat industry. An example is the stunning operation which ranges from using a captive bolt (e.g., common for beef), electrical stunning (e.g., poultry, pigs, fish), controlled atmosphere stunning (e.g., pigs, poultry), cold water stunning (e.g., fish) and no stunning in some cases (e.g., for religious slaughter), as well as large variation in conditions used within the same species (e.g., low voltage electrical stunning for poultry in N. America, vs. high voltage in Europe) due to different customs and regulations. Overall, consumer interest in animal welfare issues has substantially grown (Grandin, 2013), and now represents a powerful force that affects meat marketing in most regions of the world.

The objective of this review is to examine some of the major changes in the meat primary processing industry and relate them to scientific knowledge gained in areas such as muscle biology, chemistry and engineering while focusing on obtaining high meat quality.

2. Overview of steps in primary processing

A list of the major processing steps which apply across most animal species is shown in Table 1. Variations do exist depending on factors such as the size, presence of hair/feathers/scales, and projected end use of the meat. As mentioned above, the highest line speed is seen in poultry plants. One of the first innovations that had a significant impact on increasing poultry line speed was in the area of evisceration, which traditionally required lots of manual labour and still is done by hand in countries where low cost labour is available. In such a plant, the Roman Soldier would see hundreds of people standing along the processing line, each responsible for one/two operations/cuts. Fig. 1 shows an automated evisceration system for poultry where today >10,000 birds/h can be processed without any human intervention. Developing the equipment has allowed a major increase in line speed and mechanisation of the whole process in the 1970s (Table 2). The beef and pork industries face other challenges in the evisceration process where larger body size and animal to animal variation exists; i.e., making the execution of repeated mechanical evisceration more complex. Overall, line speed at a modern fast pork processing plant today is 1200 pigs/h as will be discussed in Section 3. Along such a line the Roman Soldier will see quite a few employees manually executing various tasks. Fig. 4a shows an example of a robotic arm being used to perform an opening cut in pigs. The robot has been recently installed in Australia with a price of $700,000. The system is guided by lasers and is supposed to be accurate, but the price tag still makes it hard to justify for many hog production facilities. That is why more automation can be seen in the pork/beef industries when it comes to cutting/slicing uniform pieces of sections without bones (e.g., loins, fillets). The equipment ranges from a water-jet knife (very high pressure narrow stream controlled by a computer) to the less expensive slicing knife controlled by laser vision. The lasers are used to determine the volume of the meat and later optimise slicing to meet pre-determined specifications. Both are examples of advanced high speed technologies already used in numerous meat processing plants (red meat, poultry, and fish) around the world. Going back to the Roman Soldier one can easily explain the

Table 1
Overview of steps in primary processing of meat producing animals.

- Live animal supply (catching, hauling, unloading)
- Stunning (bolt, electrical, CAS)
- Bleeding
- Removing hair/feathers/hide/scales
- Electrical stimulation [a]
- Evisceration
- Inspection
- Chilling
- Aging
- Portioning cutting
- Packaging and distribution

[a] Example of an optional procedure to help speed up rigor development (see text for details).

Fig. 1. Automated poultry evisceration equipment. Courtesy of Stork.

cutting operation by a conventional knife, but it would be a great challenge to explain how a laser guided knife is used to collect a 3D image of the meat, calculate densities of fat and lean meat, while using a computer (driven by electrical power) to execute the operation (e.g., cutting a few hundred slices per min with an accuracy of ± 1 g).

Overall more automation has been introduced into the poultry industry because of the smaller size and more uniform nature of broilers compared to the larger red meat animals (Barbut, 2002). Fig. 2b shows equipment used for harvesting chicken breast fillets. The equipment is mainly based on determining positions for cutting by first stretching the wings and bringing the joint to a certain position above a circular knife (i.e., cutting while the carcass is moving on an overhead conveyer belt). After several incisions are made at the edge of the fillet, the meat is pulled away (mechanical action) from the keel bone (i.e., it might sound very simple, but the development of a unique carrier that can rotate at different angles has taken quite a few years).In larger animals some of the new developments are based on locating key points by X-ray and/or ultrasound technology, prior to directing a knife to perform the cut. In any case, at the moment most of the deboning in large animals (beef, pork) is done manually. It is interesting to note that in the fish industry there are now quite a few machines for automated filleting. This is a unique application as often there can be large variations in size. However, the idea is to find the mid line and cut out the back bone while obtaining the two fillets from both sides (Fig. 2c). This is done by placing the fish in a vertical position and using guides which can assess the width of the fish (i.e., no need to use X-ray); however, the fish have to be sorted into certain weight groups in order to adjust the equipment to work properly.

Table 2
Increases in broiler processing line speed. Based on Barbut, 2010.

Year	Line speed	Comments
1970	3000	
1975	4500	New eviscerator
1980	8000	
1990	9000	Giblet harvesting
2000	10,500	Cut up machine
2009	12,000	Automated stunning
2012	13,500	

As indicated earlier, the meat industry has experienced quite a few changes in both technology and marketing. Some major examples that could be communicated to the Roman Soldier:

– Food safety → non-negotiable (Van Hoek et al., 2012)
– Sanitation and shelf life → use interventions such as: acid/steam washes, UV, radiation
– Meat tenderness → special breeds are selected for tender meat including the use of new genetic markers (Miller et al., 2010)
– Meat consumption → increased for the average person
– Distribution → moved from local to long distances (e.g., New Zealand to Europe)
– Time to prepare food at home → significantly reduced

The last item represents a major change especially over the past 50 years where the time spent by the average North American consumer to prepare food in his/her kitchen dropped from 2.5 h to 10 min today. This obviously created a huge challenge to the meat/food industry, meaning that the consumer who buys the meat expects it to be tender (not too much connective tissue; no cold shortening) free of defects (blood splashes; broken bones), and already cut into small easy to prepare portions. Another way to look at this trend is to say that it created many opportunities for the food industry to move into the semi/fully prepared food area, also known as the convenience food arena. This has developed into a huge industry that provides semi/fully cooked products to restaurants, fast food outlets, and homes (Barbut, 2010); the value of this segment is growing by several billion dollars every year and has obviously created a need for much more automation in the meat industry.

3. Understanding rigor mortis

In order to mechanise and speed up primary processing, the industry needed to learn more about the rigor mortis process (i.e., muscle stiffness after death in which energy stored within the muscle is depleted and the muscle goes into a period of being very stiff before getting pliable again). In general, the industry has gained a lot of information over the past few decades about muscle structure, composition, enzymatic processes, and conversion of muscle to meat (Scheffler et al., 2011). The explosion of knowledge and introduction of modern scientific tools have provided great insight into these topics and has made

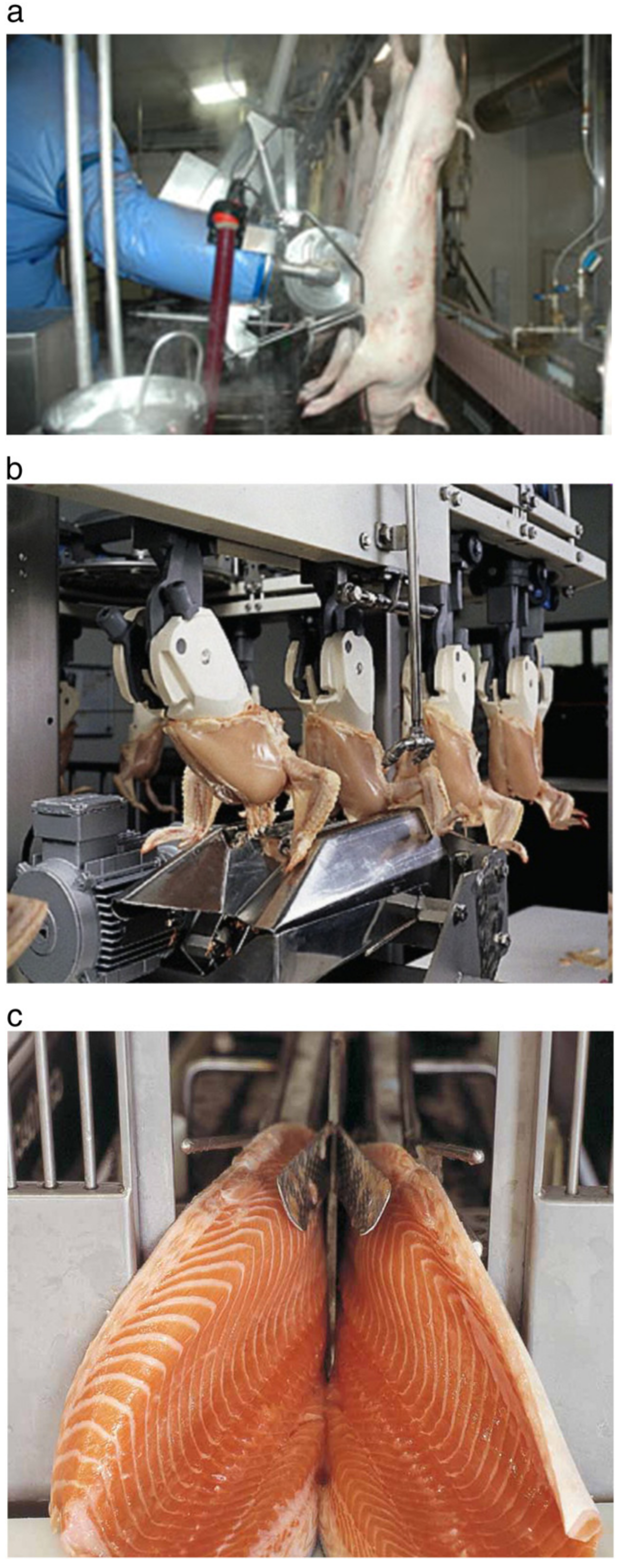

Fig. 2. Australia's first laser guided pork cutting robot installed at Craig Mostyn Group's Linley Valley (a). Automated equipment for broiler breast meat deboning (b). Automated fish back bone removal apparatus. Courtesy of Marel (c).

it possible to build equipment, optimise processes, and develop new lines for meat processing.

The overall goal of the meat processor is to go through the primary processes fast and in an efficient manner. If for example, the meat is deboned prior to the completion of rigor mortis, the resulting product is going to be tough and chewy (see reviews by Barbut et al., 2008; Scheffler & Gerrard, 2007; Simmons et al., 2008). This illustrates the point that understanding what is happening on a cellular level is important for optimizing and designing adequate equipment/processes. It is logical to assume that in Roman times people also realised that early deboning will result in low quality meat. However, recent understanding of the biological mechanisms governing the process has helped the industry to come up with innovative new high speed processes such as electrical stimulation and maturation chilling; see discussions in Sections 5 and 6 respectively. Another very important issue is the production of meat under hygienic conditions to prevent the spread of diseases from animals to humans. Until the microscope was invented by Robert Hooke in 1665, people actually did not know about the existence of microorganisms and did not fully understand the risk of diseases spreading by food and other sources.

The example provided in Fig. 1 (automated evisceration machine) also includes continuous washing of the 'spoons' used to execute the procedures; this is done after performing the task on each carcass. It should be realised that increasing line speed from 3000 to 13,500 would not allow people to follow the same standards (washing hands after treating each carcass). In addition, there is the opportunity of using strong chemicals/steam which are not allowed to be used around people. The knowledge gained in the areas of microbiology and engineering has been essential in developing such high speed equipment. When it comes to larger animals, such as pigs, the industry still relies on people to execute part/all of the evisceration. A modern line can accommodate an average of 1000–1200 pigs/h as indicated earlier. However, this usually consists of two lines handling the live animals and later merging the two into one line at the bleeding area; i.e., larger packer can process about 18,000 pigs/day. A slower line, still common at some large packers, will accommodate about 700 animals/h while a small plant will only process a few animals per day. For beef primary processing a fast line usually runs at 400 animals/h; i.e., a large processor typically handles about 5000 animals/day in two shifts. A slower line, still at some large plants, will run at about 250 animals/h. The major reasons for the difference in line speeds are related to the larger size of beef animals and higher degree of weight variation (compared to broilers). Currently both factors limit the degree of automation and affordable equipment in the primary processing area. However, it should be indicated that over the past few years quite a few improvements have been made to assist workers in red meat plants. Examples include hide pullers, lifts for employees to reach higher areas along the carcass, as well as saws and pneumatic shears suspended by cables. A laser guided pork cutting robot which has been installed in Australia (Fig. 2a) and demonstrates the growing trend of increasing automation. Currently various public research centres and commercial companies are working on developing robots for primary red-meat processing operations (e.g., DMRI in Denmark, ADIV in France, MIRINZ in New Zealand). An illustration of a modern line developed by the DMRI for pork processing is shown in Fig. 3.

Another recent example is the work of Guire, Sabourin, Gogu, and Lemoine (2010), from ADIV who studied the feasibility of cutting operations for beef and boning of a pork ham, to enhance industrial robots applications by using vision or force control. In the first part of their study, they examined the human operator expertise and looked at the persons' hand movements that looks like the letter Z (Fig. 4a), so they could work on translating the actions into automatable operative tasks, as well as identify constraints of robotisation. Later they analysed the cutting and task constraints in order to begin developing a robotic cell model. Fig. 4b shows the potential movement of the robotic cell (six-axis and a turntable) when following a path to do the so called Z-cut (shown in Fig. 4a). The first images show the non-optimised positions of the robot, and the next three images show the results of optimizing the motions, according to criteria developed in the first part of their study. Overall, the authors proposed ways to solve the problem of high variability in beef carcasses size. They also provided

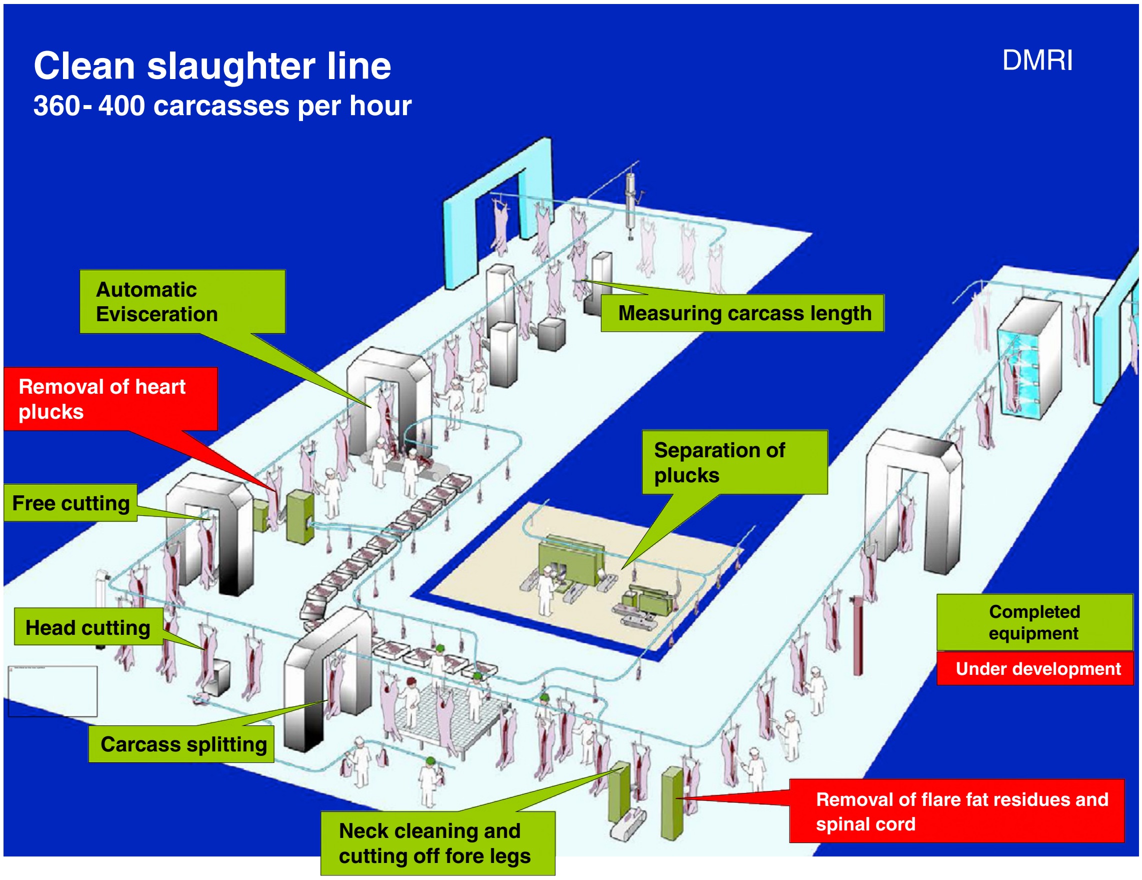

Fig. 3. An illustration of a new line design for primary hog processing. Courtesy of the Danish Meat Research Institute.

several ideas for boning pork hams, and indicated that there is a need to develop more strategies, sensors and cell architectures to make this type of complex operation. The authors concluded by saying that because of the current choices of existing industrial robots, the tool paths available (especially with force control) are limited and should be further developed so the work could be continued.

Another example is the development of a co-robot to assist workers who have to de-bone large cuts of beef. The main goals are to reduce the heavy physical demands on people by increasing the operator pull strength by a factor of 10 (Anonymous, 2011a). According to the developers, their model is going to be a two axis power assist to be used on the hook which will do 90% of the work required for pulling, tearing and/or lifting large sections of meat while allowing four additional axes of passive motion for maximum maneuverability. An example from the New Zealand sheep industry is the announcement of developing a robot to enhance meat processing (Anonymous, 2011b). This, as indicated in the article "signals the start of a new era in automated sheep meat processing" and it illustrates the interest in developing automated equipment for regions in the world where it is getting more difficult to recruit/keep staff to work in harsh environments (e.g., cold, wet), and where high labor cost and competition with other industries affect the labour market. An example of new developments in the pork industry has been presented in Fig. 3. Overall, an important point that needs to be emphasised is the difference between the current automated cutup and de-boning of poultry and red meat (beef, pork, sheep). While the former is using stretching and mechanical means to find/identify cutting locations (e.g., a joint), the latter needs development of low cost sensors, software, and algorithms to guide a robotic arm so the equipment can deal with the much larger complexity and size variations of red meat animals. This point was already briefly mentioned above, but it represents a fundamental difference in moving towards more automation in the red meat segment.

Overall, the structure of a muscle down to the sarcomere level (the smallest contracting unit) has been extensively studied over the past century, including the configuration of the thin and thick muscle filaments, which are responsible for muscle contraction. A lot of knowledge has been gained in this area, mostly in the medical field where a number of individuals were also awarded the Noble prize for their discoveries (Huxley, 1998). Trying to explain this microstructure (in the nanometer range), the biochemical processes involved and the relations to muscle texture/functionality to the Roman Soldier will not be easy and would probably take a while. In any case, understanding the processes in the living cell and later during post mortem have helped the meat industry come up with innovative solutions to speed up and manage the rate of ATP depletion, as well as achieve good meat quality at deboning time. Two examples related to the development of processes to control and/or accelerate rigor mortis are: (a) electrical stimulation which involves triggering muscle contraction and use of ATP, and (b) maturation chilling which refers to slow chilling while rigor is still going on.

The sliding filament theory is important in discussing muscle contraction in the living organism. The theory explains that physical connections are being formed and broken down between the thick filaments (myosin heads) and the thin filaments (the actin molecules) while energy is generated by several chemical pathways with the primary ATP molecule as an intermediate. Although the process of converting chemical energy (consumed as food) into mechanical energy (movement of the muscle) is very complex, understanding the process in general terms and relating it to meat science (Aberle, Forrest, Gerrard, & Mills, 2001; Scheffler & Gerrard, 2007) is crucial to our views of the induction of rigor mortis and its resolution after a few hours. Fig. 5 shows a typical graph of the process where the muscle is initially pliable and progressively becomes stiffer as time goes on. In brief, the stiffness is explained by the depletion of the energy reserves within the muscle, and getting to a point where most (>90%) of the actomyosin

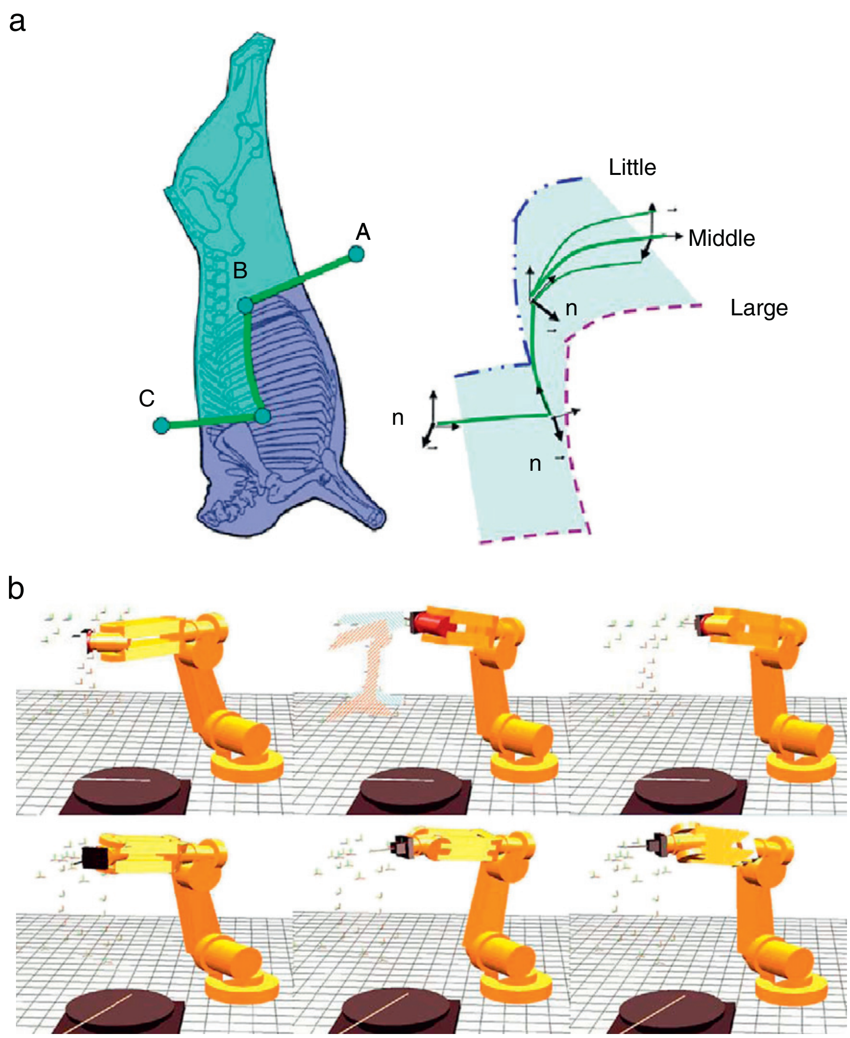

Fig. 4. Illustration of the splitting of hind and forequarter in beef also known as the z-cut (a). Movement of a robotic cell when following the z-cut (b); see text for explanation. From Guire, Sabourin, Gogu, & Lemoine 2010.

connections/bridges are formed, but cannot be broken down. The resolution of rigor mortis (e.g., decline of muscle tension and muscle becoming pliable again) is due to proteolytic enzymes degrading the structure.

Cold shortening will take place if the muscle goes into rigor while the temperature is too low. This is an example of a practical problem that sometimes is still being seen in the industry when meat goes too fast into the cooler, or the cooler is operating at too low temperatures

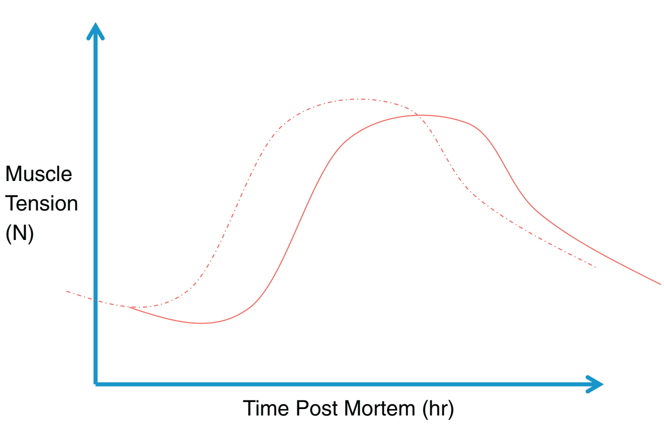

Fig. 5. Development of rigor mortis expressed as muscle tension over time. The dotted line represents speeding up the process. See text for details.

(e.g., not adjusted to the volume of meat). A more severe case is the thaw shortening that will happen if the muscle is frozen prior to the completion of the rigor mortis process. During defrosting it will result in a fast release of calcium ions which will cause a massive contraction of the structure and substantial squeezing out of water from the meat (Aberle et al., 2001). The classical studies of Locker and Daines (1976) with muscle entering rigor at different temperatures, showed minimal shortening at 15 °C (for excised muscle) which correlates well with minimal meat toughness (Tornberg, 1996). This correlation is interesting as elevated temperatures not only increase toughening due to heat shortening, but also reduce tenderisation (Devine, Wahlgren, & Tornberg, 1999). Above 12–15 °C, a contracture occurs at rigor, and below this temperature a contracture occurs before rigor. Thus the shortening effects above 15 °C are a consequence of rigor shortening only, and occur when muscles become depleted of glycogen. As the temperature falls below 12 °C a pre-rigor contracture takes place until rigor is completed. This arises from increased cellular calcium (from the sarcoplasmic reticulum) with falling temperature that in turn activates actomyosin ATPase. The rise of calcium in the cytoplasm, under these conditions, is due to the failure of the sarcoplasmic reticulum to sequester cytoplasmic calcium and is different to the transitory rise in 'free' calcium that occurs after electrical stimulation. The balance of calcium, under the latter conditions, is potentially an important factor in the activation of enzymes such as the caplains. Electrical stimulation is a solution invented by meat scientists and includes the application of external stimuli to speed up the rigor process by triggering muscle contraction and use the ATP stored in the muscle, as will be discussed in Section 5.

As meat toughness and the progress of rigor are very important issues to the industry, various methods/devices have been developed to measure rigor. The methods include measuring the tension of the muscle during rigor (similar to results shown in Fig. 5), measuring the pH, as well as following shear force (using a blade to determine the force required to cut a given amount of meat) at different stages during rigor. Measuring sarcomere length (e.g., by microscopy or by laser) and its relations to sensory toughness is also used by meat scientists and industry personnel. It should be pointed out that under similar conditions, the rate of rigor mortis is different among different animal species. Generally speaking, the delay time before the onset of rigor mortis can be rated as chicken < pork < beef; i.e., the time for chicken is <1 h, pork 1–3 h, and beef 6–12 h after slaughter (Aberle et al., 2001).

The rate and extent of postmortem pH decline during rigor significantly influences meat quality (Scheffler, Park, & Gerrard, 2011) as glycogen is converted to lactic acid. In the 1950s it was recognised that hastened glycolysis contributed to high muscle temperature and acidity, and caused the development of more pale, soft, and exudative (PSE) pork meat (Briskey & Wismer-Pedersen, 1961). The PSE problem can be manifested during the rigor process, especially in animals susceptible to stress, where the pH drops very rapidly during early post mortem; e.g., automation while dealing with a large number of animals might result in more stress to an individual animal. The pork industry has identified several genes responsible for PSE meat (see reviews by Barbut et al., 2008; Scheffler & Gerrard, 2007). One of the first genes to be discovered was the so called Ryanodin, which is related to a problem with the calcium channels within the cell. Identifying the gene has helped the industry remove susceptible animals from the herd. This is an example of using advanced molecular biology to assist meat industry processes. On the other hand, in the poultry industry which is also experiencing the PSE problem, no major genes impacting this kind of a meat quality issue are currently known to be segregating in the population. In this case, the industry relies more on measures to reduce pre-mortem stress and later also employ various processing techniques to minimise the problem (it is interesting to note that according to the literature, PSE can affect 5–30% of a broiler flock depending on factors such as hot weather, transportation distance, health, and meat chilling conditions). Examples of steps used by the industry to reduce the problem include: providing a rest period to the broilers after transportation to the processing plant (see discussion of the automated CAS stunning system in Section 4), and use of starches/hydrocolloid gums in the cooking process (Barbut et al., 2008). Beef tends to show more of the opposite problem known as dark, firm, dry (DFD) meat, which results from struggling and exhaustion prior to slaughter and high post mortem pH. Again, when a large number of animals are being moved/processed, more stress to an individual animal can occur. The problem can sometimes reach up to 2%. Overall exhausted animals (prior to slaughter) start with low glycogen in the muscle (i.e., the precursor for lactic acid formation and pH reduction). Understanding this process has helped the beef industry in developing resting pens and mechanical showers to reduce stress prior to slaughter.

It should also be mention that not all animals that show low post mortem pH are affected by the PSE condition. Monin and Sellier (1985) reported that animals with greater initial muscle glycogen content, or also known as "high glycolytic potential", show an increased capacity for post-mortem glycolysis, which leads to an extended pH decline and lower ultimate pH. This is largely based on the elevated muscle glycogen and low ultimate pH ("acid meat") conditions observed in the Hampshire pig breed. These rapid and extended pH declines in post-mortem muscles negatively impact protein characteristics, albeit by different mechanisms, and thus generate inferior pork meat. Subsequently, "early" and "ultimate" pH measurements have been embraced by the industry as indicators of meat quality, and both can be used for automated control of initial processing conditions.

4. Stunning

Although stunning is applied early in the process it can directly affect meat quality at later points along the chain. Stunning is usually mandated to render the animal unconscious prior to bleeding. Different methods are used depending on the size of the animal, local regulations, and industry requirements, but all have to assure proper welfare and meat quality. The most common methods include captive bolt (commonly used for beef), electricity (commonly used for poultry, pigs, and some fish), control atmosphere stunning (CAS; used for pigs, poultry, and some fish) and cold water (used in some species of fish). Earlier it was indicated that the introduction of CAS has helped to increase line speed for poultry (Table 2) as the system can be semi or fully automated. The equipment was developed to process a large number of birds without human intervention. Prior to that, small crates with broilers had to be unloaded by hand and birds caught by their feet were placed on a moving shackle line. In a fully automated system, a large cage tilting mechanism eliminates the need for catching conscious birds and placing them on a moving shackle line. The reader is referred to the review by Gregory (2008) for an interesting discussion about introducing automation to this phase of the process in the form of the CAS system developed for poultry. It should be mentioned that an automated system for electrical stunning of fish is available, but there is no fully automated system for large animals such as cattle or pigs.

CAS systems for poultry are based on either inducing a single phase hypercapnic anoxia, a two phase system (Coenen, Lankhaar, Lowe, & McKeegan, 2009) or low atmosphere stunning. In the anoxia system an inert gas such as nitrogen or argon is used. In the two-stage stunning the first stage includes enrichment with 30% O_2 and 40% CO_2 (CO_2 is used as an anesthetic gas during the first phase) followed by a second phase of 80% CO_2 (Fig. 6a). In the low atmosphere, air is removed from the environment. The unconscious birds are later picked up and placed on a moving shackle line for bleeding. There are also CO_2 systems on the market for pigs (Fig. 6b). All systems can help reduce labour costs and increase mechanisation of the process. However, incidents of convulsion and animal welfare issues should be carefully monitored. An example of a study focusing on welfare is shown in Fig. 7 where the results indicate the time for unconsciousness, wing flapping, and convulsions (both can also cause damage to the carcass) for different CAS gas mixtures used for broilers. The results indicate that the two stage stunning process results in the least amount of convulsions. The authors recommended that method as it results in fewer convulsions (seen in Fig. 7 as intense black spikes) after birds became unconscious. It should be mentioned that currently in Europe CAS is becoming very popular for broilers (until a few years ago electrical stunning was the main method and still is in North and South America, Asia and Africa). Part of the reason is the requirement for higher voltage and lower frequency for stunning poultry in Europe (i.e., due to of animal welfare issues). This requirement results in a deeper stun but can also result in more damage to wings and meat quality (e.g., blood spots in the white fillets). From January 2013 the new EU regulations also specify the mA required for stunning each individual bird (e.g., 110 mA per broiler; EU Regulation 1099/2009). This has been done for animal welfare reasons, but also represents a major change in the EU regulations, which highlights the point that the meat industry has to respond to new regulations in order to assure animal welfare, meat quality, sanitation standards, etc.

5. Electrical stimulation

Electrical stimulation was developed originally in New Zealand in the late 1970s to manage toughening in lambs that were being frozen

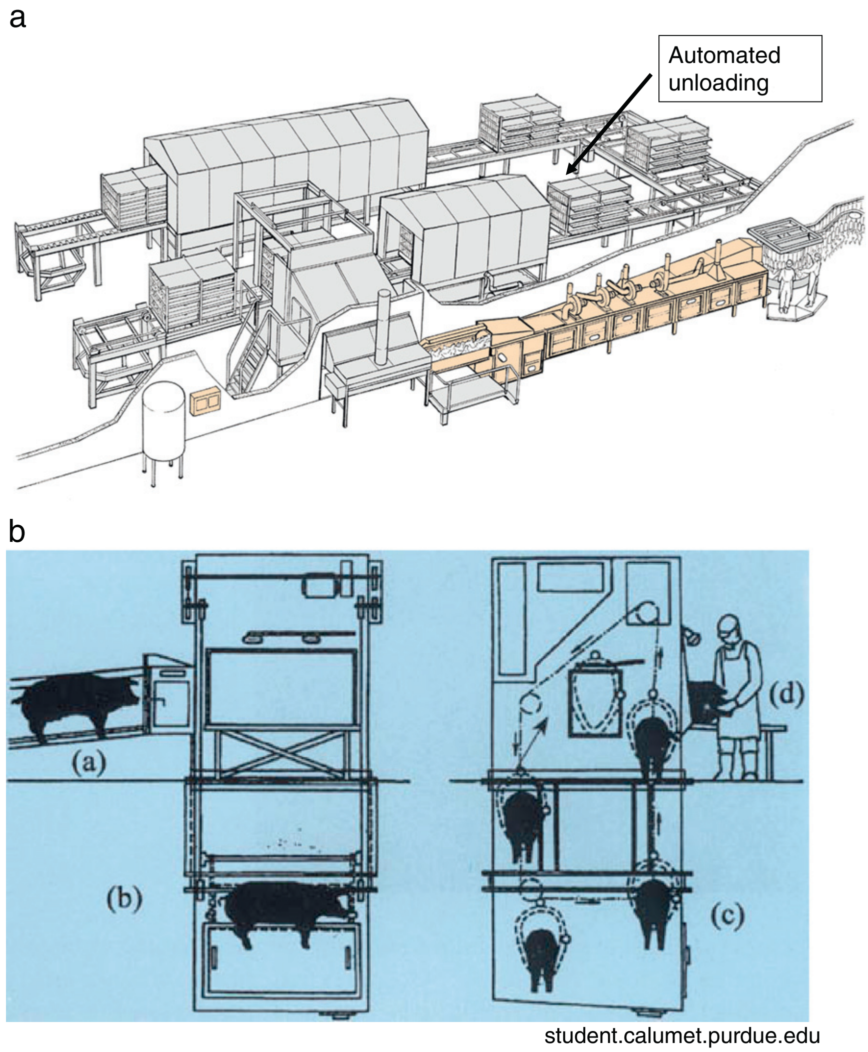

Fig. 6. An automated controlled atmosphere stunning system for (a) poultry and (b) hogs. For poultry the large modules are unloaded with a fork lift, placed on a conveyor belt that moves forward and then tilts the birds onto a wide belt that takes them through the CAS tunnel. No manual labour is required (except inspection for dead/injured birds). The system can process 13,500 birds per hour. Courtesy of Stork. For hogs a mechanical device lowers the pig into a pit with CO_2 (i.e., CO_2 is heavier than air).

rapidly after slaughter; i.e., an extreme cooling regime that clearly produced cold-shortening and its associated toughening (see Section 3). The need to process a large number of lambs and maintain long shelf life during shipment/export drove this practice. Cold-induced contracture can be measured at temperatures as high as 25 °C, although its severity increases as the temperature decreases further (Davey & Gilbert, 1975; Honikel, Roncales, & Hamm, 1983), so some level of cold-shortening is likely to be commonplace in carcass processing. But the true benchmark of cold-shortening, and its commercial significance (persistent toughening), requires a level of contracture in excess of 20% of the sarcomere's rest length (Davey & Gilbert, 1975). As the industry sometimes still faces problems with tough beef after applying conventional electrical stimulation at the beginning of the process, innovations such as Smart-Stimulations (Simmons et al., 2006 to be discussed below) have been very helpful in automating the process, delivering the precise stimulation to each carcass and improving uniformity.

Earlier, electrical stimulation was applied to lamb and beef only, but today it is popular in poultry (especially over the past 10 years) and some fish species, to shorten the rigor period. In chicken processing it allowed the development of a continuous in-line processing, where broilers can be deboned within 3.5 h after bleeding as opposed to 6–8 h without electrical stimulation. In this case the birds are kept on a moving shackle line during the entire process. That by itself saves labour and money (dropping and rehanging) as well as streamline the process (birds weighed and graded by an automated image analysis system just after de-feathering/evisceration so decision about cutting up or keeping as a whole bird can be made 3 hrs prior to the actual deboning time).

The electric current triggers the muscles to contract, increasing the rate of glycolysis and resulting in an immediate fall in pH. Electrical stimulation of a beef carcass can routinely drop the muscle pH by 0.5 units over a stimulation period of 60 s, a process that could require 3 or more hours in the absence of stimulation (Ducastaing, Valin, Schollmeyer, & Cross, 1985). This represents a 180-fold acceleration in the rate of muscle glycolysis and a clear indication of the tight coupling between the rate of glycolysis and ATP turnover in a muscle tissue. The energy of activation of ATP in stimulated beef *M. sternomandibularis* was calculated to be 97 kj/mol (Chrystall & Devine, 1985). Following the pH there is a temperature dependent acceleration of glycolysis (dpH/dt) and subsequent early rigor mortis development.

When automating the processing line it is important to realise that rigor does not occur across all muscles simultaneously with a concomitant fall in pH. Jeacocke (1984) showed that for single fibres, there was a contracture as the final ATP disappeared (i.e., rigor) and each fibre had its own time course, depending on initial glycogen. A small temperature-dependent degree of contraction occurs for each muscle

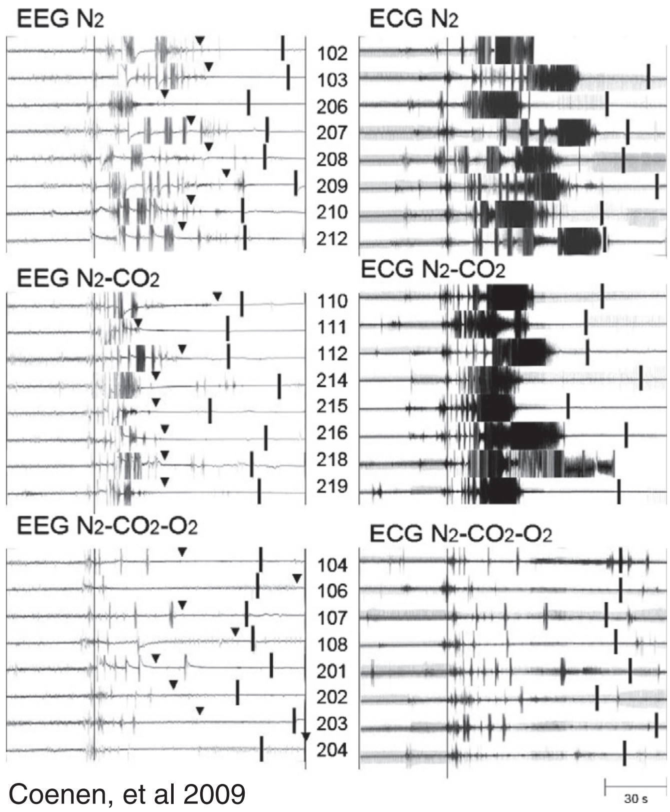

Fig. 7. Effect of different gases used during a control atmosphere stunning operation of broilers. Showing traces of heart and brain reactions. EEG—Electroencephalogram; ECG—Electrocardiogram; N_2—Nitrogen; CO_2—Carbon Dioxide; O_2—Oxygen. From Coenen et al., 2009.

fibre, and could be tracked by measuring isometric tension and muscle shortening. Stiffness is a consequence of each single fibre going into full rigor, with irreversible cross bridge formation of the contractile components, actin and myosin. With increasing numbers of fibres entering rigor, the stiffness increases (Fig. 5) and is becoming significant when the muscle reaches a pH of approximately 6.0. At some stage the bulk of stiff muscle prevents significant shortening, of fibres not in rigor, from a cold contracture (if exposed to low temperatures).

As electrical stimulation is used to activate muscle contraction by an outside stimulus, one must understand animal physiology, electricity, resistance, wave forms, etc. in order to apply it effectively and without damaging meat quality. Different voltages and regimes are used for different species and also within the same species. In beef, reports of high (300–500 V), intermediate (145–250), and low (45–110) voltage have been described in the literature (Hwang, Devine, & Hopkins, 2003). Frequencies range from 14 to 160 Hz and amperages, if measured at all, from 0.5 to 6 A (Swatland, 2012).

It is also important to know that the muscle has other backup energy sources (e.g., creatine phosphate) which can provide energy after/before all of the ATP is consumed by the muscle. This is one of the reasons why repeated stimulation is applied and why after conventional electrical stimulation some muscle contraction can still be seen.

The review by Simmons et al. (2008) examined the current theories about the effect of stimulation on post-mortem muscle. The classical view that stimulation prevents muscle from shortening, especially during rigor development has been expanded to include the possibility that it also results in physical disruption of muscle structure (Hwang et al., 2003). Emphasis was also put on the interactions of these effects on accelerating proteolysis through activation of the calpain protease system. Earlier, Simmons et al. (2006) developed a system called Smart Stimulation in New Zealand. The system allows tailoring stimulation parameters (number of times, strength, and duration) to the needs of a specific beef or lamb carcass while the carcass is moving on the line (i.e., in line processes without interruption to flow). Feedback from probing the carcass, by sending an electrical pulse, may result in the system delivering additional 15 s stimulation to one carcass and 60 s to another. The automated computer system measures the response of the carcass during stimulation and, from the nature of the response, derives information about the pH of key muscles (particularly the *Longissimus thoracis*). By repeatedly testing the state of the carcass, during the stimulation process, it is possible to stop the stimulation when the pH has reached the designated level. Two components have to be added to a conventional stimulation procedure: (a) load cells mounted on the stimulation rail, at certain intervals, to allow the response characteristics to be measured, and (b) introduction of defined test pulses of the standard 15 Hz stimulation waveform. The interrogation of the carcass response to the test pulse is measured via the load cells and analysed, by a computer, in real-time. The decision regarding the requirements for subsequent stimulation levels are generated via specialised algorithms embedded in the control software. Overall, this is an example of an automated system that has helped deliver the required pulses for each carcass, and reduce variations in tenderness.

6. Chilling

Chilling of meat can have pronounced effects on tenderness (Locker & Hagyard, 1963), as well as yield. Generally speaking, large red meat carcasses are chilled by air while suspended on an overhead shackle line, while smaller broiler/turkey carcasses can be chilled either by air or water. In the case of water chilling, carcasses can be suspended from a shackle line or dropped into a long screw/paddle type cold water bath where they are slowly moved to the end point (speed can be adjusted to control chilling duration). All of these movements are basically automated in large processing plants. Maturation chilling is an example of a development which illustrates the importance of combining biological sciences and engineering. Originally, small carcasses such as poultry were chilled by immersion in large tubs filled with water and ice. Later a long chiller with a device to advance the carcasses has been introduced. This was followed by introducing the concept of counter flow pattern (clean cold water flow from the exit side) to improve efficiency and hygiene of the meat. The use of cold air for large scale poultry operations has been developed later. Today the need for a continuous in-line operation demands fast and efficient processes, preferably without removing the carcasses from the line. Maturation chilling has been developed to achieve these goals without sacrificing quality. Broiler carcasses stay on the line, while the outside is initially fast-chilled with a stream of very cold air directed to the thick parts, followed by a period of exposure to slower moving air at a slightly higher temperature, which does not interfere with the rigor mortis process (see previous section dealing with cold shortening). This is an important point in understanding how to automate a meat processing plant, as dropping the birds into a water bath and later re-hanging them onto a shackle line breaks the flow. It is estimated that the cost of re-hanging (done manually) is 5–10¢ per bird. Dropping the birds from the line (as is done in most water chill operations) also results in losing their identification number. This is important if initial image analysis is used to evaluate and grade the birds (i.e., after evisceration); note: most companies supplying large scale processing equipment have such a camera system in their portfolio. The system allows making early decisions and forward planning about end product use (whole bird, cut up bird), 3.5 h before the birds arrive to the cut up area. This information and ability to plan ahead is worth quite a lot of money to the processor. In this example, combining maturation chilling, electrical stimulation and automated stunning system, has allowed efficient and economical deboning of broilers at 3.5 h after bleeding, without meat toughening problems. The whole integrated process is often called ‘tender-management’ and is becoming popular in new built plants as well as some renovated plants. This is a significant improvement over the older practice (which is still used today in quite a few places), where the plant operator had to wait for 6–10 h for the completion of rigor mortis prior to deboning (i.e., usually results in the next day deboning). The accelerated process requires understanding of muscle metabolism during the post mortem process as well as an investment in hardware for a long continuous line to be built so birds stay on the line for the entire process (no dropping from the line and no need for a buffer zone typically used during a 6–10 h processing time). The red meat (beef and sheep) industry is also commonly using electrical stimulation and/or the Smart Stimulation (the latter is currently only popular in New Zealand and Australia) and with that is able to significantly reduce time to deboning, save space and energy (e.g. reduce chilling cost of heavy bones). They also chill on a moving line so carcasses are on the rail (held in a cooler for 6–24 h), which eliminates removing and rehanging cost, as well as allowing tracking and tracing of animals (mandatory in quite a few countries today). A commercial computerised system capable of tracking all of that will be discussed in Section 8.

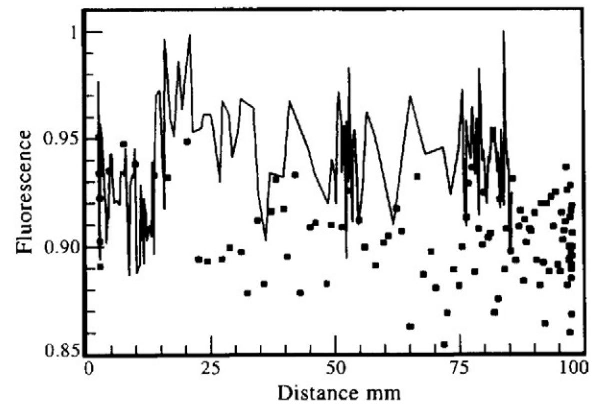

Fig. 8. Data from a fiber optic probe used to evaluate the amount of connective tissue in meat. The probes moves into the meat (X axis shows distance form surface), and records fluorescence reflection when going through layers of connective tissue. From Swatland & Findlay, 1997.

7. General attributes—genetics and other developments

Eating quality of meat is very important to the modern consumer where food is part of the culture of enjoyment. Back in Roman times food was mainly consumed for survival by the average person, and issues such as meat toughness or juiciness were not as important as getting the meat itself. Today consumers are willing to pay premium price for high quality, tender meat cuts they consume at home or in an upscale restaurant. Therefore, there is much emphasis on producing highly tender meat cuts. In addition to the approaches mentioned above about achieving tender meat, mechanical tenderisation is another method the industry is employing to guarantee that certain cuts (e.g., beef round which traditionally presented a challenge to the industry) are sold without a problem. In Canada for example, a fairly large portion of the retail fresh beef cuts are going through mechanical tenderisation at the meat packing plants. This kind of tenderisation involves automated machines with an overhead plate, in which multiple narrow needles/blades are inserted. The meat is moving on a conveyer belt and the needles inserted at pre-determined intervals; used to physically disrupt the connective tissue. This results in less resistance to shear and improves consumer satisfaction.

Several protease enzymes have also been commercialised: bromaline (from papaya), papaine (from pineapple), and ficin (from figs). These enzymes help to break down the connective tissue structure and can be used on the surface or injected into thick cuts of meat. Their activity should be controlled, as over use can result in meat which is falling apart. Activating or speeding up some of the internal proteases in the muscle (e.g., calpain) is another approach mentioned already in Section 5. Overall, meat scientists are looking for processes that will assure tender meat. At the same time, scientists/engineers are busy developing on-line methods/probes to quickly measure/predict meat quality parameters (e.g., texture by mechanical means, flavor/aroma by an electronic nose). Some probes rely on the optical properties of components within the meat, such as a probe for fast prediction of the amount of connective tissue in the muscle (Fig. 8). The idea is that when the probe is inserted and crosses a layer of connective tissue it can pick up a signal from the collagen, which is illuminated at one wavelength and reflects light at another (i.e., based on collagen fluorescence characteristics).

Geneticists are also busy in identifying genes associated with tender meat where beef animals are the main focus (Miller et al., 2010). Pork meat does not show too many problems with toughness and this is not a major consumer issue when consuming meat from relatively young animals. In the case of beef, animals were selected in the past based on being able to work and walk (e.g., the big cattle drives in the U.S.). During the past half a century special breeds have been identified and producers can now guarantee a certain degree of tenderness (e.g., the certified Angus beef program), and the USDA is working on a new tenderness certification program (Yates, 2013). In general *Bosindicus* (e.g., Brahman) breeds tend to be tougher than *Bostaurus* breeds (Angus, Hereford) as *Bosindicus* has greater amounts of calpastatin. Selection for certain breeds and animals within a certain breed have helped to improve consistency over the years. However, it should be realised that many factors are involved and interactions with animal's activity, nutrition, and ageing time, can complicate the situation. Recently the use of single nucleotide polymorphism (SNP; pronounced 'snip') technology has become popular. Researchers are using units with a few thousand SNPs to correlate the presence of certain genes for traits like tenderness (measured as shear force values). Miller et al. (2010), reported on an experiment where 1000 beef animals were screened with a 50,000 SNP chip and several domains have been identified. In their study, a domain for calpastatin had been identified and patented as a marker for tenderness. In the future it is envisioned that marker-assisted management will become common place (e.g., a few hundred SNPs will be used to screen and select animals for traits such as tender meat and high milk production).

Garrick (2011) indicated in his review that genomic prediction aims at reducing errors at breeding age (by exploiting information on the transmission of chromosome fragments from parents to selection candidates). This in conjunction with knowledge on the value of every chromosome fragment, should speed up the process. In the past, beef cattle selection has not been so efficient, in achieving balanced improvement across the spectrum of traits that contribute to breeding goals. One reason has been the inability to cost-effectively rank selection candidates for all the attributes of interest. This is the case because the reliability of quantifying the merits of animals has been totally reliant on recording pedigree and performance information, primarily on the selection candidates themselves, their parents and perhaps their offspring. In the beef cattle context, this has led to low selection accuracy for mature size, lifetime reproductive performance, stayability/longevity, and disease resistance. Other important traits such as tenderness, overall eating quality, and feed efficiency, have had no prospects for selection as there are no phenotypic measures that could be readily and cost-effectively obtained on large numbers of seed-stock animals. Therefore, molecular-based information is now promising to improve the prediction of young animals by first using phenotypic markers, second using microsatellite markers, and most recently using ever-increasing densities of SNPs. For example, a commercial genomic testing service is now using the results from the analysis of an Angus population, to market a panel comprised of a subset of informative SNP referred to as a 50 k-derived product (marketed by Igenity in the US in conjunction with the American Angus Association and costs only $65). Other genomic tests for genes related to beef tenderness have been developed and are now available after they have been validated through the National Beef Cattle Evaluation Consortium (www.ansci.cornell.edu/nbcec).

In 2004 the chicken genome project was completed. This meant that the chicken was genetically charted; i.e., on each of the 39 pairs there are thousands of genes; altogether about 20,000 which contain about 1.5 billion base pairs. As with the beef mentioned above, SNPs are used as genetic markers. There are 15 to 20 million SNPs in a chicken (each covering two sequences consisting of 100 to 200 bases). Of interest is that two joint base sequences can be different by one base only, (i.e., one sequence has a C and the other sequence has a T at the same location). Recently automated equipment has been developed to read the SNPs, and the cost went down to approximately 0.2 cents per SNP (Bijleveld, 2011). Genetic markers are also used today to trace animals and later meat from a specific animal in cases of a food borne outbreak. Overall, it is expected that this technology will become more common in the future and further help the industry.

8. Concluding remarks

Combining the knowledge generated by animal physiologists, meat scientists, nutritionists, engineers, veterinarians, animal welfare specialists and marketing people has helped to move the industry forward. As demonstrated in this review we have advanced a long way in terms of increasing line speed, tenderness, and shelf life.

New computer control systems are finding their way into meat processing plants where they are used to control a single operation, a processing area, or the entire plant. Sophisticated software programs for an entire meat plant, record results and show data in real time (materials coming in, inventory, flow of material within the plant, up-to-date yield figures, and even the efficiency of an individual employee on the deboning line). Such systems require multiple inputs and sensors (e.g., resistance of meat to electrical stimulation, amount of connective tissue in a specific cut, weighing stations, colour, pH, fat content measurements). One of the biggest advantages of having real-time information is in reducing cost by increasing efficiency and minimizing waste. It is interesting to mention that in the past the further processing industry has made significant advancements with programs such as the Least Cost Formulation Program (used to formulate multiple products from a variety of incoming raw materials). Some of the first programs were introduced about 30 years ago when mainframe computers appeared on the market. However, today many computers, software programs and some robotic operations are seen in the primary processing segment. In the future it is expected that more control systems will be introduced and new sensors will be developed. In any case, they will all have to be based on sound meat science principles. Explaining all these new technologies to the Roman Soldier would be an even greater challenge, but so would be the cars parked outside the meat plant, and aircrafts/spaceships flying above.

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References

Aberle, E. D., Forrest, J. C., Gerrard, D. E., & Mills, E. W. (2001). *Principles of meat science* (4th ed.)Dubuque, Iowa: Kendall/Hunt Publishing Company.

Anonymous (2011a). Kinea design and Scott technology selected by MLA to lead development and commercialization of world's first beef boning co-robot. Available at: http://www.kineadesign.com/news/pressrelease/mla-ha/ (Accessed June 20, 2012).

Anonymous (2011b). The world launch of the first robot for automated sheep processing. Available at: http://halal-focus.net/2011/03/29/nz-theworld-launch-of-the-firstrobot-slaughterman/ (Accessed June 20, 2012).

Anonymous (2012). Industrial revolution. Available at: http://www.wikipedia.org/wiki/IndustrialRevolution (Accessed June 20, 2012).

Barbut, S. (2002). *Poultry products processing. An industry guide.* New York, NY: CRC Press.

Barbut, S. (2010). Advances in primary poultry meat harvesting. *World's Poultry Science*, *66*, 399–410.

Barbut, S., Soznicki, A. A., Lonergan, S. M., Knapp, T., Ciobanu, D. C., Gatcliffe, L. J., Huff-Lonergan, E., & Wilson, E. W. (2008). Progress in reducing the pale, soft and exudative (PSE) problem in pork and poultry meat. *Meat Science*, *79*, 46–63.

Bijleveld, H. (2011). Genomic selection brings more genetic progress. *World Poultry*, *27*(5), 18–20.

Briskey, E. J., & Wismer-Pedersen, J. (1961). Biochemistry of pork muscle structure. 1. Rate of anaerobic glycolysis and temperature change versus the apparent structure of muscle tissue. *Journal of Food Science*, *26*, 297–305.

Chrystall, B. B., & Devine, C. E. (1985). Electrical stimulation: Its early development in New Zealand. In A.M. Pearson, & T. R. Dutson (Eds.), *Advances in Meat Science*, *Vol. 1*. (pp. 73–119)Westport: AVI Publishing Co.

Coenen, A.M. L., Lankhaar, J., Lowe, J. C., & McKeegan, D. E. F. (2009). Remote monitoring of electroencephalogram, electrocardiogram, and behaviour during controlled atmosphere stunning in broilers: Implications for welfare. *Poultry Science*, *88*, 10–19.

Davey, C. L., & Gilbert, K. V. (1975). Cold shortening and cooking changes in beef. *Journal of the Science of Food and Agriculture*, *6*, 761–767.

Devine, C. E., Wahlgren, N. M., & Tornberg, E. (1999). Effect of rigor temperature on muscle shortening and tenderisation of restrained and unrestrained beef m. longissimus thoracicus et lumborum. *Meat Science*, *51*(1), 61–72.

Ducastaing, A., Valin, C., Schollmeyer, J., & Cross, R. (1985). Effects of electrical stimulation on post-mortem changes in the activities of two Ca dependent neutral proteinases and their inhibitor in beef muscle. *Meat Science*, *15*(4), 193–202.

Garrick, D. (2011). The nature, scope and impact of genomic prediction in beef cattle in the United States. *Genetics Selection Evolution*, *43*, 17–28.

Grandin, T. (2013). Design of loading facilities and holding pans. Available at: http://grandin.com/references/design.loading.facilities.holding.pens.html (Accessed May 15, 2013).

Gregory, N. G. (2008). Review—Animal welfare at markets and during transport and slaughter. *Meat Science*, *80*, 2–11.

Guire, G., Sabourin, L., Gogu, G., & Lemoine, E. (2010). Robotic cell for beef carcass primal cutting and pork ham boning in meat industry. *Industrial Robot: An International Journal*, *37*, 532–541.

Honikel, K. O., Roncales, P., & Hamm, R. (1983). The influence of temperature on shortening and rigor onset in beef muscle. *Meat Science*, *8*(3), 221–241.

Huxley, A. (1998). How molecular motors work in muscle. *Nature*, *391*, 239–240.

Hwang, I. H., Devine, C. E., & Hopkins, D. L. (2003). The biochemical and physical effects of electrical stimulation on beef and sheep meat tenderness. *Meat Science*, *63*, 677–691.

Jeacocke, R. E. (1984). The kinetics of rigor onset in beef muscle fibers. *Meat Science*, *11*, 237–251.

Locker, R. H., & Daines, G. J. (1976). Rigor mortis in beef sternomandibularis muscle at 37 °C. *Journal of the Science of Food and Agriculture*, *26*, 1721–1733.

Locker, R. H., & Hagyard, C. J. (1963). A cold shortening effect in beef muscles. *Journal of the Science of Food and Agriculture*, *14*, 787–793.

Miller, S., Lu, D., Vander Voort, G., Sargolzaei, M., Caldwell, T., Wang, Z., Mah, J., Plastow, G., & Moore, S. (Aug 1–6). Beef tenderness QTL on BTA25 from a whole genome scan with SNP 50 bead chip. *Proceedings from the 9th Annual World Conference on Genetics Applied to Livestock Production. Aug* (pp. 1–6). http://www.kongressband.de/wcgalp2010/index.html (Leipzig, Germany).

Monin, G., & Sellier, P. (1985). Pork of low technological quality with a normal rate of muscle pH fall in the immediate postmortem period: The case of the Hampshire breed. *Meat Science*, *13*, 49–63.

Scheffler, T. L., & Gerrard, D. E. (2007). Mechanisms controlling pork quality development: The biochemistry controlling postmortem energy metabolism. *Meat Science*, *77*, 7–16.

Scheffler, T. L., Park, S., & Gerrard, D. E. (2011). Lessons to learn about post-mortem metabolism using the AMPK$\gamma 3^{R200Q}$. *Meat Science*, *89*, 244–250.

Simmons, N. J., Daly, C. C., Cummings, T. L., Morgan, S. K., Johnson, N. V., & Lombard, A. (2008). Reassessing the principles of electrical stimulation. *Meat Science*, *80*, 110–122.

Simmons, N. J., Daly, C. C., Mudfort, C. R., Richards, I., Jarvis, G., & Pleiter, H. (2006). Intergrated technologies to enhance meat quality—An Austrialasian perspective. *Meat Science*, *74*(1), 172–179.

Swatland, H. (2012). Basic science for carcass grading. Available at: www.3.sympatico.ca/howardswatland/Brazil/htm (Accessed June 20, 2012).

Swatland, H., & Findlay, C. J. (1997). On-line probe prediction of beef toughness, correlating sensory evaluation with fluorescence detection of connective tissue and dynamic analysis of overall toughness. *Food Quality and Performance*, *8*, 233–234.

Tornberg, E. (1996). Biophysical aspects of meat tenderness. *Meat Science*, *43*, 175–191.

Van Hoek, A. H., de Jonge, R., van Overbeek, W. M., Bouw, E., Pielaat, A., Smid, J. H., Malorny, B., Junker, E., Lofstrom, C., & Pedersen, K. (2012). A quantitative approach towards a better understanding of the dynamics of *Salmonella* spp. in a pork slaughter-line. *International Journal of Food Microbiology*, *153*, 45–52.

Yates, L. (2013). Agriculture marketing service's beef tenderness certification program. *66th Reciprocal Meat Conference* (pp. 11). Auburn University.