Objective carcass measurement technologies: Latest developments and future trends

Gonzalo Delgado-Pando, Paul Allen, Declan J. Troy, Ciara K. McDonnell

PII: S0924-2244(20)30728-7

DOI: https://doi.org/10.1016/j.tifs.2020.12.016

Reference: TIFS 3068

To appear in: *Trends in Food Science & Technology*

Received Date: 14 April 2020

Revised Date: 24 August 2020

Accepted Date: 13 December 2020

Please cite this article as: Delgado-Pando, G., Allen, P., Troy, D.J., McDonnell, C.K., Objective carcass measurement technologies: Latest developments and future trends, *Trends in Food Science & Technology* (2021), doi: https://doi.org/10.1016/j.tifs.2020.12.016.

Objective Carcass Measurement Technologies: Latest Developments and Future Trends

Gonzalo Delgado-Pando[a], Paul Allen[a], Declan J. Troy[a], Ciara K. McDonnell[a,b]*

[a]Teagasc Food Research Centre Ashtown, Dublin 15, Ireland
[b]CSIRO Agriculture & Food, 39 Kessels Road, Coopers Plains, QLD 4108, Australia

* Corresponding author – ciara.mcdonnell@csiro.au

Abstract (word count max. 250)

Background

Carcass evaluation is a key process to ascertain the value and the quality characteristics of the animal at slaughter. In addition to being the base for monetary transactions between livestock producers and meat processors, in some countries, this evaluation also helps to determine the market allocation of cuts. Recent advances in non-invasive techniques are being tested for their potential to improve classification and grading systems in the meat industry.

Scope and Approach

In this review, global grading and classification practices for pig, sheep and beef carcasses are discussed along with the latest technological developments in objective carcass measurement. We discuss a number of studies predicting marketable attributes such as yield (lean and saleable meat yield), eating quality attributes (inter- and intramuscular fat, meat and fat colour) and carcass dimensions (skeletal structure, ribeye area). Technologies based on x-ray, nuclear magnetic resonance, video image analysis, ultrasound, bioelectric impedance and spectroscopy are discussed, along with recent developments and their possible future adoption.

Key findings and conclusions

DEXA and magnetic induction technologies have been commercialised for the sheep and pig industries, respectively. X-ray technologies and updates in VIA systems could go beyond grading to improve yield and cut dimension predictions. Some technologies could improve process efficiencies through cut sorting and enabling robotic cutting, while also enabling improved value-based payment systems. However, there are challenges associated with their implementation in meat processing plants and further research and development is required in some areas.

Keywords (6 max):

Grading
Classification
Meat prediction
Automation
DEXA
VIA

1. Introduction

Evaluation of carcass characteristics is a key process in order to ascertain the quality and the value of the animal at slaughter. Classification systems are those which aim to place a carcass into a class based on descriptors, while grading aims to sort the carcass based on merit, thereby grading has a value element (Allen, 2009; Mitchell, 2019). The grading appraisal is the basis for transactions between livestock producers and meat processors and in some countries, the evaluation helps to determine the market allocation of different cuts (Allen, 2009). However, the system used is country dependent, with some systems based on yield prediction, and others that include quality characteristics. A good value-based payment system can lead to the transfer of more accurate price signals throughout the supply chain where there are clear financial incentives for producers to breed animals with attributes that are desired by consumers (Allen, 2009).

Subjective evaluation based on standards was the starting point for classifying carcasses, but in an attempt to improve consistency and accuracy, and move towards advanced value-based systems, some countries have introduced objective carcass measurement (OCM). Studies have been conducted on OCM prediction of both lean meat yield (LMY) and saleable meat yield (SMY). LMY is defined as the percentage lean muscle tissue in a carcass while SMY, in modern and practical terms, is defined as the meat trimmed to a specification whereby it is ready for the point of sale. As SMY is specification dependant (i.e. market) and includes variation in quantities of lean and fat and may also include bone, it is more difficult to standardise than LMY. However, some developments in prediction systems have taken place. Eating quality OCM differs as it is a multicomponent attribute (tenderness, juiciness and flavour) as perceived by the consumer (Allen, 2009) but some predictive technologies for objectively measured tenderness have been studied and these are discussed in the later sections.

Due to the 4th industrial revolution, the rate of advancement in OCM technologies and commercial uptake has accelerated in recent years, as has the meat industry‘s requirements and willingness to adopt new technologies. This is driven by the need for automation and improved process efficiency, which require an understanding of the composition and characteristics of the carcass earlier in the process (Narsaiah, Biswas and Mandal, 2020). Another fundamental driver is to reward producers for animals that more closely align with market/consumer demand. A detailed review of several OCM technologies for meat: Dual x-ray absorptiometry (DEXA), Computed Tomography (CT), Magnetic Resonance Induction (MRI), and Ultrasound (US) can be found in Scholz, Bunger, Kongsro, Baulain and Mitchell (2015). Further, Narsaiah et al (2020) provide an overview of broader applications of nondestructive methods for carcass and meat evaluation, which in addition to grading attributes also considers contamination, disease and storage evaluation. The objective of this review is to describe more recent advances in OCM technologies that align with current global practices and therefore could soon emerge to offer improvements in existing commercial objective grading systems or complementary systems for subjective grading. Furthermore, we broaden the scope to developments in other non-commercialised technologies that have limited studies completed on meat applications but could have future potential. In doing so, we aim to provide insight into future developments that could have an impact on the meat industry.

2. Carcass grading and classification

A thorough and historical review of global grading and classification systems can be found by Polkinghorne and Thompson (2010). In this section, we provide a brief summary, outlining recent developments, of the classification and grading schemes of the countries with large production and export markets.

Carcass evaluation emerged as the quality control needed for the commercial transactions between livestock producers and meat processors. Carcasses are now rarely sold to retailers as a whole; the carcasses are broken down into different cuts and sorted to meet the demands of various markets and retailers. Better knowledge of carcass quality and composition can lead to better allocation of cuts to markets according to their specific demands. Carcass quality covers several factors that can affect the future visual and sensory characteristics of the meat, whereas carcass evaluation usually means variables related to the yield of a carcass. Attributes such as marbling, fat depth and cover, pH, temperature, hanging method, tropical breed content, hormonal growth promoters, texture, and lean and fat colour relate to carcass quality. Yield determination focuses on maturity, eye muscle area, weight, sex, fat level and carcass conformation. Depending on the country and type of animal, the specifications for carcass classification and grading will vary. A summary of the different grading systems and the measured attributes can be found in Table 1. Various objective technologies are already in use in carcass evaluation systems and these are summarised in Figure 1 and discussed in later sections.

Beef carcass classification systems can be divided into those which include eating quality grade and those which focus on carcass yield evaluation. Among the countries without eating quality grades are the European Union (EU), most of the MERCOSUR countries and South Africa (Table 1). The EU implemented the EUROP Classification System in 1981 under the European Economic Community Regulations (EEC) No. 1208/81 and No. 2930/81 which ensured uniform classification and price reporting for the member states. This system focuses on carcass yield estimation by visual assessment of the carcass shape known as conformation (from superior to poor) and subcutaneous fat cover (from low to very high) with 5 categories of each. It has been shown that the current EUROP grading system does not indicate marbling and additional indicators for palatability should be applied in the European beef industry (Liu et al., 2020).

On the other hand, countries like Australia, Canada, Japan, South Korea and USA have grading systems that, in addition to yield, include visual and/or eating quality attributes (Table 1). The Australian system grades the carcass based on standards for meat and fat colour, quantity of marbling, eye muscle area, rib fat and the maturity of the carcass as defined by AUSMEAT (AUSMEAT, 2018). An additional system developed by Meat & Livestock Australia and known as Meat Standards Australia (MSA) (MLA, 2016), is a predictive eating quality model based on consumer sensory data, which aims to grade individual cuts according to a cooking method. This method has recently been described as the ‘Gold Standard’ of eating quality grading for beef (Mitchell, 2019). The ability of the MSA system to predict eating quality outside of Australia has been demonstrated through EU research projects (ProSafeBeef and ProOptiBeef) and in other countries (France, Poland, Ireland, Northern Ireland, Japan, South Korea, New-Zealand, the USA and South Africa) (Bonny et al., 2018). Recently, the ability of the MSA system to grade meat quality in Poland was successfully demonstrated in a study whereby Polish consumers categorised the eating quality grades of grilled beef at 6 mm and 25 mm thickness (Pogorzelski et al., 2020). The ability of more countries to grade for eating quality using a standardised method could become a reality with the recent establishment of International standards for eating quality. The International standards for carcass assessment and consumer testing have been accepted by the United Nations Economic Commission for Europe (UNECE) Bovine Language Standards and through the work of the International Meat Research 3G Foundation, training on beef eating quality grading systems can be accessed globally. The goal is to develop an international predictive model of beef palatability (Hocquette et al., 2020; Polkinghorne, 2019).

With regard to sheep carcasses a similar approach to beef classification is followed by most countries (Table 1). In Europe and South Africa sheep carcasses are classified following the same characteristics as in bovine: carcass weight, age, conformation and fat cover. In Australia, the AUS-MEAT system also adds the depth at the GR site (110mm from the carcase midline over the 12th rib) and the MSA establishes certain standards (in terms of carcass weight, fat class, GR depth, pH and ageing) and categorises the carcasses according to their dentition. The MSA system also includes the appropriate cooking methods for each cut, however development in the MSA EQ grading for sheep is far less extensive than the beef system (Pannier, Gardner, O'Reilly, & Pethick, 2018).

In most countries, pig carcasses are classified according to a lean meat yield estimation mainly based on measures of carcass weight and fat thickness. Only the Japanese Meat Grading Association (JMGA) have a secondary grade assessment for pig carcasses. This is based on drip, texture, meat and fat colour and marbling. In the EU, pig carcasses must be classified, based on the lean meat yield of the carcass, according the SEUROP scale under EC regulation No 1249/2008, which was updated as being mandatory for plants processing more than 150 carcasses per week as an annual average in Commission Delegated Regulation (EU) 2017/1182.

The next sections review technological developments which have been applied recently or have potential to be applied to the classification and grading of sheep, beef and pig carcasses.

3. Latest developments in non-invasive methods for the determination of body and carcass composition:

3.1. X-ray based technologies

X-ray technologies are based on the different degrees of attenuation of the x-rays as a consequence of the different densities of the body/carcass tissues (lean muscle, bone, fat). In the following sub-sections the most employed x-ray technologies by the meat industry will be discussed.

3.1.1. Computed Tomography (CT)

In the late 1960s, Dr Godfrey Hounsfield deduced that if an x-ray beam was passed from all directions onto an object, getting all the information from all the x-ray transmissions will lead to the observation of the object's internal structure. This was the origin of computed tomography (CT). Since then, four generations of CT scanners have been developed. In the current CT systems, the x-ray source rotates and the attenuation, after passing through the object, is measured by stationary ring detectors, thus enabling the generation of 3D images after data processing by a computer. The tissues of interest: fat, muscle, and bone, all have different mass attenuation coefficients that are transformed into CT numbers or Hounsfield units (HU). The HU increases with increasing density such that fat, water and bone have average HU units of -50 to -100, 0 and 700-3000, respectively, whereas muscle usually ranges between 0-140 (Scholz et al., 2015).

The first applications of CT scanning in meat-producing animals were for estimating the body composition of live pigs (Kolstad and Vangen, 1996; Font-i-Furnols et al., 2015). With recent technologies and chemometrics, values of the prediction accuracy have improved (as defined by the coefficient of determination R^2 and/or root mean square error). Coefficients of determination (R^2) are as high as 0.98-0.99 for protein, moisture and fat, while the root mean square errors of prediction (RMSEP) are 0.63, 1.03 and 1.14 for protein, moisture and fat percentages, respectively (Font-i-Furnols, Carabus, Pomar, & Gispert, 2015). Today, CT is recognised as the ‘Gold Standard’ in determining the LMY of carcasses. As such, it is recognised under EU Commission Regulation (EC) No 1249/2008 as one of the calibration methods for other online classification devices such as ultrasound, optical probes and magnetic induction (Olsen, Christensen, & Nielsen, 2017). Research has focused on new applications beyond being a calibration tool. As shown in Table 2, CT has been applied for the determination of carcass composition (Matika et al., 2016; Navajas et al., 2010), intramuscular fat (IMF) (Clelland et al., 2018; Font-i-Furnols, Brun, & Gispert, 2019; Font-I-Furnols et al., 2014; Lambe et al., 2017) and cut weights (Font-I-Furnols et al., 2014). Other studies on CT scanning include the prediction of fat and lean weights from primal cuts of growing pigs (R^2=0.994 and 0.993 for fat and lean, respectively) (Carabus, Sainz, Oltjen, Gispert, & Font-i-Furnols, 2015) but Font-i-Furnols et al. (2019) found that intramuscular fat (IMF) prediction from CT images of live pigs had medium to low accuracy (RMSEP=0.56-0.66). However, more recently, Font-i-Furnols et al. (2020) found out that CT was a suitable technology for determining pig carcass composition before slaughter. Another recent application has been the creation of a 3D model pig atlas from the live animal for delineating the anatomy of porcine organs, skeleton and muscles (Ho, Yu, Gangsei, & Kongsro, 2019). In sheep meat research, the use of CT scanning has been applied in a genome-wide association approach whereby CT-measured productivity traits were studied for their association with molecular polymorphisms in UK Texel sheep (Garza-Hernandez et al., 2018).

Even though CT scanning is a good tool with the ability to differentiate between tissues of interest in the animal, carcass or primal cuts, there are several limitations to its application and these present challenges for it being an on-line method. Some overlap may appear in animals as some tissues have similar HU, such as mammary tissue and fat, skin and meat and fat and marrow (Olsen et al., 2017; Scholz et al., 2015). It is important to note that differences in the operating protocols and manufacturers/brand of scanners can present problems when comparing the results from different experiments. Thus, standardisation of these protocols and selecting the mass attenuation coefficients is essential. There is a need to further standardise the HU to reduce uncertainty in CT results (Olsen et al. 2017). This could be achieved by developing phantoms that mimic the different tissue densities and then adjust the settings per HU depending on the outcome. But even with that harmonisation there will still be more sources of uncertainty such as the image reconstruction by the software (dependent on the brand) and the image post processing used to classify the pixels into the desired tissues (Olsen et al., 2017).

In addition, medical CT devices are not currently practical on-line in meat processing due to cost, operational speed and safety issues. Systems must be operated in lead-lined rooms to protect operators from radiation leakage, and parts are expensive to replace. The gantry aperture is usually <1m in diameter which precludes scanning entire beef sides over a certain weight. Nonetheless, there are recent developments aimed at improving the usefulness of CT in the meat industry. An online CT unit for application on meat cuts (0.5m aperture) has been developed which removes the safety concerns for operating CT because the unit is contained. The unit works at a speed of up to 600 samples per hour and has no cooling requirement. It could be developed for multiple applications in the boning hall such as automated sorting of high-value cuts based on eye-muscle area, improved trimming accuracy or intramuscular fat prediction (DTI, 2017). Another potential commercial application is the use of CT to predict IMF with high precision (R^2 =0.86, RMSE=2.01) (Cook & Anderson, 2017) and it has been demonstrated to predict IMF more accurately than the MSA marbling score (R^2=0.89 v 0.81) (Anderson, Cook, Williams, & Gardner, 2018). This could offer the ability to objectively determine some parameters of eating quality prediction. In the same trial, algorithms were devised to enable automation tasks by locating specific carcass locations. Described as an opportunity that could offer the meat industry a ‘quantum leap’, approaches are being devised to test CT scanners from the aviation industry for meat industry application (Seaton, 2017) which could overcome many hurdles associated with on-line CT. It is evident that a lot of research has been devoted to CT use in meat production animal studies over the last decades. It remains the most promising technology for determination of lean, fat and bone portions and for providing 3D images of meat cuts so if future developments can operate at line speed, vertically and address safety concerns, it could have a future role in carcass grading, beyond being a calibration tool.

3.1.2. DEXA

Dual x-ray absorptiometry (DEXA) couples the x-ray information acquired at two energy levels (high and low) and was initially designed for the measurement of bone mineral density. The main parameter collected after the scan is the difference (ratio) between the attenuation from the high- and low-intensity x-ray, the so called R-value. The individual pixels are divided into two types: pixels from soft tissue (no bone) and pixels with bone. The R-value is used to determine the fat content from the former and the bone content from the latter, whereas the lean content is estimated as a difference between the two (Pomar, Kipper, & Marcoux, 2017). Bone mineral content and bone mineral density can also be obtained.

Due to its high accuracy, DEXA has been repeatedly used for compositional studies in live pigs, carcasses and cuts (Bernau et al., 2015; Kremer, Fernandez-Figares, Forster, & Scholz, 2012). In general, the use of DEXA for predicting sheep body or carcass composition has been deemed to be accurate and effective (MacGhee et al., 2017).

Several research studies have elucidated the possible information that can be gained from DEXA such as the estimation of body composition in live calves (MacGhee et al., 2017) and to predict the lean and fat of the 9-11th rib cut in beef (Prados et al., 2016). López-Campos et al. (2017c) estimated via linear regression the lean, fat and bone content from beef carcasses (R^2 =0.88, 0.95, 0.53, respectively) and primal cuts using DEXA. When the authors used partial least square regression for the prediction, the coefficients increased to 0.98. The lean prediction for most of the primal cuts had $R^2 > 0.94$ whilst for fat, the R^2 were > 0.91 excluding the fore-shank. The prediction of total and saleable yield of beef carcasses has been recently evaluated in 316 half-carcasses by the same group (López-Campos et al., 2017b). The accuracy of prediction of total carcass lean and fat was higher (R^2 =0.98) than saleable yield of the loin, rib and chuck (R^2 from 0.7 to 0.97).

As with CT, standardised processes are required. A comparison of two different DEXA instruments for the estimation of body composition in 77 live pigs showed significantly different lean, fat and bone predictions between instruments (Losel, Kremer, Albrecht, & Scholz, 2010). Therefore, inter-comparisons require a prior cross validation in order to be able to make the data from particular studies comparable. In addition, the accuracy will be affected by species related and other factors. Scholz, Kremer-Rücker, Wenczel, Pappenberger, and Bernau (2013) compared the accuracy of the same DEXA instrument for the estimation of fat and meat in different species (61 pigs, 93 lambs and 34 calves). Not surprisingly, predictive accuracy was higher for the carcass than for *in vivo* animals, and generally was also higher in pigs, followed by lambs and then calves. DEXA estimation of body composition *in vivo* was strongly affected by the content of the gastrointestinal tract, being much higher in ruminants than in non-ruminants such as pigs. In another species-related study, using the same device, López-Campos et al. (2017a) presented a comparison of the DEXA accuracy for carcass composition in 230 beef steers, 104 cows, 155 lambs and 212 pigs using the same instrumentation and procedure. RMSE for fat percentage was the lowest in cows (0.0987) and highest in lamb (0.1478), while similar for steers and pigs (0.1160, 0.1133, respectively). In the case of lean, the lowest RMSE was for steers (0.0913), followed by pigs (0.0954), cows (0.1182) and lambs (0.2085).

Another issue is the beam hardening effect, when for example using thick and/or very dense samples, the lower energy photons are attenuated and only the higher energy ones contribute to the beam resulting in artefacts on the image. A study by Kipper, Pomar, Marcoux, and Radünz Neto (2015) showed that the thickness of meat samples affected the percentage of fat, soft tissue and lean mass estimated by DEXA but did not affect the estimation of fat mass. It must be noted that the level of water in fat-free tissues could also present a problem when using DEXA technologies as this ratio is considered to be constant and changes in body weight are an important factor (Pomar et al., 2017). For example, drip loss from the carcass is a factor to be considered, especially at commercialisation, depending on the post-mortem time of analysis.

Prediction of LMY by DEXA has reached commercialisation in the lamb industry with several units being installed in New Zealand and Australia and recent studies have demonstrated that it is a superior method for fat prediction in sheep carcasses than standard GR measurements which are used in Australia with good results for fat (R^2=0.91, RMSE=1.91%) when compared to CT determination (Connaughton et al 2020). Much of the development work was conducted through the Advanced Livestock Measurement Technologies (ALMTech) programme in Australia, a genetically and phenotypically diverse subset (n=559; 2-4 mm GR tissue depth, 10.9 - 39.3 kg hot carcass weight (HCW)) of carcasses were selected and CT scanned for calibration of DEXA which resulted in R^2 of fat%, lean% and bone% of 0.89, 0.74 and 0.71 and root-mean square errors of 1.42, 1.69, and 0.80, respectively (Gardner et al., 2016). Trimmed cuts were also CT-scanned and algorithms were derived to predict the cut-weight, with DEXA estimating the weight of most commercial cuts with an R^2 >0.85 (Williams et al., 2017). This could offer processors the ability to predict the weight of commercial cuts prior to bone-out and therefore allow sorting according to market demand (Williams et al., 2017).

The application of DEXA to predict fat percentage in beef has also been assessed. When using a prototype DEXA system in a shipping container, 51 beef carcasses were CT and DEXA scanned to determine a DEXA value to predict CT fat%. DEXA estimates described 88% of the variation in whole carcass CT fat% (RMSE=3.21) (Gardner et al., 2017). DEXA has been proven as an effective method for the determination of LMY in sheep, and future work on a large data set could lead to improved RMSE values for beef. Commercially, it has also been successfully coupled with robotics for automated cutting of sheep carcasses, leading to accurate cutting, the possibility of improved yield on higher value cuts and a reduced incidence of operator injuries. However, the system often requires a large footprint and must be constructed in lead-lined rooms for staff safety. Furthermore, it provides LMY information on the chilled carcass so in countries which require conformation scores on a hot carcass for grading, other systems will be required. Nonetheless, DEXA has potential to provide information about market specific traits on certain cuts and to inform robotic systems so it could become a more common technique to grade carcasses based on LMY. However, it’s uptake will be processor specific as decisions to invest in the technology will be based on factors such as throughput (i.e. payback timeframe), factory space, if automated cutting is desired and governance of grading in that country.

3.1.3. Others

There are other x-ray based technologies that have been used for compositional determinations in meat products. Transmission radiography, the simplest x-ray approach, has been used to estimate total fat and salt content in hams (de Prados et al., 2015). Frisullo, Marino, Laverse, Albenzio, and Del Nobile (2010) used micro-CT for the rapid estimation of

IMF in five different commercial cuts obtaining high correlations ($R^2 > 0.92$) with chemical fat content.

Hoban et al. (2016) utilised small angle x-ray scattering synchrotron technology for the determination of ovine meat quality. The authors found that this technology could moderately determine myofibrillar characteristics related with meat tenderness and to evaluate the differences of IMF in ovine carcasses.

Recent advances in x-ray technologies have focused on increasing image resolution, or utilising robotics (rotating x-ray) and enabling phase contrast x-ray imaging (PCI). PCI provides complementary information in addition to conventional attenuation-based imaging and allows for enhanced tissue characterization, such as quantification of protein, lipid, and water content within each 3D voxel (Willner et al., 2016). However, these applications have not yet reached commercialisation.

3.2. Nuclear Magnetic Resonance (NMR) based technologies

3.2.1. Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) is based on NMR and involves transforming the signal information into 3D grey scale images. MRI is based on spatial localization of the NMR signal by a Fourier transformation. MRI images are generated by classifying the tissues according to the relaxation times of protons (T_1 and T_2). These two constants provide different intensities of images: while white matter is brighter than grey matter in T_1-weighted images, it is darker in T_2-weighted images (Carabus, Gispert, & Font-I-Furnols, 2016). The former acquisition is performed first, and only if it does not give enough contrast, the T_2-weighted acquisition is performed as it requires longer sequences. There are two types of MRI scanners: low and high field. Low field scanners (also known as open scanners) operate at around 0.23 T (Tesla), while high-field ones (or closed MRI) can operate up to 3 T. Better and more rapid resolutions are obtained with closed MRI. The tissue structures present in meat — muscle, fat, and connective tissue — can be exceptionally well differentiated using MRI in a volumetric way (Baulain, 1997). The vast majority of the literature using MRI in animal science is focused on live pigs, scanning the live animal at selected points (loin, thorax region, ham) and obtaining the correlations with body components (Bernau et al.2015; Kremer et al., 2012). Recently, Bernau, Schwanitz, Kremer-Rücker, Kreuzer, and Scholz (2018) used MRI to analyse different body composition traits (including testis volume) in live pigs and compared them to boar taint indicators (androsterone, skatole, and indole levels) post-slaughter. It was found that entire boars had larger testis volumes and belly fat and these were associated with higher levels of androsterone.

Both closed and open MRI have a maximum bore diameter of 70 cm (wide bore MRI), although most instruments have 60 cm diameter. Due to these size constraints, beef carcasses cannot be analysed if they have not been previously cut into primals. Lee et al. (2015) used MRI in beef cuts purchased from a local market to observe if prediction of marbling was accurate. The results showed a strong correlation between the chemically measured IMF and the MRI determination (R^2=0.986). The authors also pointed out the potential use of MRI to measure the distribution of IMF. This would be advantageous as there is no analytical method that can do this. As previously mentioned, IMF is currently assessed, both subjectively and objectively, in some countries on the rib-eye cross section and this only serves as an indicator of marbling throughout the muscle. Therefore, an objective method that could determine IMF would be favourable for eating quality grading. Despite the good resolution and accuracy of MRI, there have been limited experiments on meat due to the size constraints, the high cost of the instrument and the longer times for data acquisition, when compared to other devices.

The most important advances in MRI have been in the software, increasing the scan speed and the image quality. In the USA, a high-field MRI of 7T has been approved, doubling what was available previously (Fornell, 2016). Another innovation came from researchers at the University of Aberdeen who developed a Fast Field Cycling MRI, which is described as being like a hundred MRI's at once (Abdn, 2017). The unit, which is based on the deliberate switching of magnetic fields, was developed through the EU Horizon 2020 programme under the project IDentIFY. By switching magnetic fields, opposed to constant frequency in standard MRI, very detailed images are achieved. The first commercial application is for medical imaging but it serves as an example of the advancements in the field. Similar to CT, commercialisation of MRI for meat grading will only be likely if several hurdles such as cost, safety, resolution at high speed and ability to analyse larger animals are addressed.

3.2.2. Magnetic Resonance Spectroscopy and Quantitative Magnetic Resonance

NMR can also be used for spectroscopy applications. In this process, magnetic resonance spectroscopy (MRS) aims to separate and measure different metabolites on the basis of the variation in resonance frequencies of nuclei with different magnetic environments (Baulain, 1997). In animal science, the hydrogen proton is most frequently used but ^{31}P and ^{13}C have also been employed to give insight into energy metabolism. A low field and more affordable MRS is the time domain (TD)-NMR, that has been successfully applied to small samples (~15g) of meat for fast prediction of quality characteristics (Pereira et al., 2013). In addition, it was recently reported that TD-NMR has the potential of being applied as a beef eating quality grading instrument as it provided good linear predictions for fat (0.88), moisture (0.79) and drip loss (0.79) and a promising correlation with tenderness (0.58) (Webster, 2019).

Quantitative magnetic resonance (QMR) is a relatively new non-invasive and non-imaging method that is still in the evaluation phase for farm animals. The difference from MRI is that the scan takes place at once in the whole body and the time domain signal rather than the spectrum, is processed directly (Mitchell, Ramsay, & Scholz, 2012). One of the advantages of QMR results is that they are not dependent on the hydration of the fat-free tissue, as opposed to DEXA, although an underestimation of fat content can occur (Bosy-Westphal & Muller, 2015). QMR has been successfully employed for assessing changes in body composition of piglets (Mitchell et al., 2012) but as this is one of the less explore technologies for meat application, further research is required.

3.3. Bioelectromagnetic Methods: Bioelectrical Impedance Analysis (BIA), Total-body electrical conductivity (TOBEC) and Magnetic Induction (MI)

The electromagnetic properties of the animal, carcass and meat are highly correlated with the fat tissue content and therefore bioelectromagnetic technologies could be applied to understand the animal or carcass composition. Adipose tissue has lower water content and ions than any other tissue in the animal, hence it is a poorer conductor of electricity. Bioelectrical Impedance Analysis (BIA) involves placing contacts on the animal and measuring the reactance (capacitance) and resistance (resistive) that are used to calculate impedance. Total-body electrical conductivity (TOBEC) differs from BIA in that it does not involve the use of electrodes but a surrounding coil is utilised instead, generating a radiofrequency electromagnetic field that is absorbed in proportion to body conductivity (Allen & McGeehin, 2001). Based on the same principle, Magnetic Induction (MI) measures the small perturbations of a variable magnetic field due to the passage of a body through it (Ellis, 2001).

BIA has been used to predict free-fat mass in buffalo calves obtaining high accuracy (R^2=0.967) (Sarubbi, Baculo, & Balzarano, 2008). More recently, Silva et al. (2018) obtained good prediction of carcass composition in young goats using BIA. When combined with other parameters such as carcass length, and carcass cold weight, it accurately predicted carcass fat weight (R^2=0.94), intermuscular fat weight (R^2=0.95) and chemical fat content (R^2=0.86).

TOBEC accurately predicted the lean meat percentage in beef leg primals and pork carcasses (RSD=2.08 % and RSD=1.97 %, respectively) (Allen & McGeehin, 2001). It can also be used for body composition prediction (fat free lean and protein mass) in live animals with high accuracy (R^2 =0.94) (Simeonova, Todorov, & Schinckel, 2012). Simoncini et al. (2012) used MI equipment (Lenz Fat-Analyzer™) to predict the lean content of hams obtaining high accuracy (R^2 =0.90), while a lower accuracy (R^2 =0.80) was found for pork bellies using an updated version (HAM-Inspector II™) of the aforementioned equipment (Daumas, Monziols, Rodriguez, Alvarez-García, & Causeur, 2019).

Despite the high accuracy and relative safety (electromagnetic field is really low), the use of TOBEC and MI by the meat industry is scarce and mainly focused on ham grading and the estimation of chemical lean in boxed manufactured meat (Allen & McGeehin, 2001). The two main reasons slaughterhouses might have not invested on these technologies are that the tunnel is horizontal and also too small to fit a whole beef carcass (Allen & McGeehin, 2001). However, the EU recently approved the use of MI for SEUROP grading of pig carcasses in Spain and Poland (GMSteel, 2018). The system (gmSCAN) has been designed for slaughter plants as it is upright (vertical), contactless and can process 900-1000 carcasses per hour. Using multiple transmitter coils to generate a variable and low intensity magnetic field, the lean meat yield can be calculated due to the differences in the dielectric properties of fat and bones compared to lean in a certain range of frequencies. The system obtained a RMSEP of

1.94% for the prediction of LMY in pig carcasses following a trial on 130 carcasses in Spain. The concept is based on the use of contactless MI to measure the dielectric properties of the carcass. In the calibration trials, the system also predicted the LMY and weights of primal cuts. The prediction error obtained for the LMY was 1.7% for the ham, 1.98% for the belly, 1.74% for the shoulder and 2.15% for the loin. In addition, the unit could predict the weight in the primal cuts with prediction errors for the ham of 372g, 257g for the belly, 148g for the shoulder and 255g for the loin. While the technology has been successfully developed and commercialised for pig carcasses, it would be interesting if future studies assess its applicability to sheep and beef carcasses.

3.4. Ultrasound (US)

Ultrasound (US) is based on the reflection of sound energy when it encounters any physical material. There are two types of applications, as a non-destructive diagnostic tool (>1MHz) or as a processing technology (~20-100 kHz). For the latter, high-intensity US (10-1000 W/cm^2) is employed, while high frequency (>100 kHz) low-intensity (<1 W/cm^2) US is used as a non-destructive analytical tool for quality control.

High correlations between the US measurements on the live animal with corresponding measurements on the carcass have been found for ribeye area in cattle (R^2 up to 0.92) (Scholz et al., 2015), subcutaneous fat in sheep (R^2 up to 0.95) (Silva, 2017) and IMF in pigs (R^2 up to 0.92) (Carabus et al., 2016). Table 3 shows the range of US applications including prediction of carcass and quality characteristics to genetic improvement in pigs, sheep and cattle.

A Danish company, Frontmatec Smoerum A/S (formerly known as Carometec A/S, Smorum, Denmark), launched in 1994 the first 3D automatized US device (Autofom™) that allowed the on-line grading of pig carcasses by LMY predicted from hundreds of backfat thickness and muscle thickness measurements. It was authorised for use in France, Hungary and the UK (Carometec, 2017). The recently improved version of the model (Autofom™ III) has now been authorised as a grading system in Belgium, Denmark, Ireland, Finland, Germany, Italy, Poland, Spain and Sweden. Outside the EU, Choi et al. (2018), used the Autofom™ III to predict primal and commercial cut weights in pig carcasses. Calibration models for deboned shoulder blade, shoulder picnic, loin, belly, and ham demonstrated R^2 of 0.77 to 0.86 but other groups of cuts did not perform as well (spare rib, back rib, jowl, false lean, and diaphragm cuts resulted in $R^2 < 0.34$). Nonetheless, as demonstrated and discussed by Choi et al. (2018), the Autofom™ III is more accurate than its predecessor (Autofom™ I) and demonstrates that technologies are advancing towards improved accuracies.

Within ultrasound imaging, there is a direct relationship between sound frequency and image quality. Shorter wavelengths give better resolution, but longer ones are needed to reach more depth in the tissue. The current focus is on transducer improvement so that they become smaller and easier to use.

Even though this technology is very advanced in pigs (suitable on-line due to wet skin after the scalding process ensuring good acoustic contact), the same technology cannot be implemented on beef or sheep carcass due to air pockets following de-hiding which would impede proper access of the sound energy (Allen, 2009). Addis et al. (2020) tried to predict hind-leg muscles weight of yearling dairy-beef steers with ultrasound measurements of EMA obtaining low percentage of variability explained (39.9%). Therefore, it is likely that applications on sheep and beef will only be useful on live animals, while it is a successful pig carcass grading technology.

3.5. Video Image Analysis (VIA)

VIA systems are based on the differences in light intensity received by a video camera (e.g. fat from lean meat). In a detailed review by Craigie et al. (2012), the evolution and development of VIA for beef carcass evaluation is thoroughly discussed. VIA technology can be divided into two groups; a hand-held VIA system which can be used for quality grading (typically IMF), rib-eye area, colour and fat thickness measured at the quartering site of the carcass and whole-carcass VIA systems which can assess carcass attributes related to yield or composition (fat cover, conformation). In 2007, the USDA approved the first VIA hand-held systems to determine rib-eye area, marbling score and the quality grade at the 12th-13th rib (Woerner & Belk, 2008). Recent studies have assessed the ability of the VGB2000 to grade beef carcasses in other countries and adapt it to a different grading location on the carcass. For example, Schulz and Sundrum (2019) demonstrated that with some software modifications, the VGB2000 could grade for marbling in German beef carcasses (n=354) with a regression coefficient (R^2) of 0.78 (grading at the left and right side at 10-11th rib*)*. The same system has recently been assessed for its ability to predict MSA marbling score, fat thickness and rib-eye area (Langbridge, 2018). The VIA system correlated with an expert plant grader for marbling (R^2 =0.682), fat thickness (R^2 =0.689) and rib-eye area (R^2 =0.782). The MIJ-30 grading camera (Meat Image Japan, Japan) is another VIA system for grading quality attributes. Kuchida, Sakaguchi, Kano, Goto, and Komine (2018) tested the ability of this device to measure IMF percentage and rib-eye area obtaining a high correlation with visual grade scores (R^2 =0.964 and R^2 =0.926, respectively).

In Europe, Oceania and South America, whole-carcass VIA systems from four different companies have been adopted for beef grading: VBS 2000 (E+V GmbH), VIAscan (Cedar Creek), BCC-2.1 (Carometec A/S) and MAC-S (Normaclass). The first three systems were tested by Allen and Finnerty (2000) on 7247 beef carcasses. These systems (VBS 2000, VIAScan and BCC 2.1) were able to predict EUROP conformation and fat classification scores and saleable meat yield with acceptable accuracy. The percentage of confirmation classifications within one subclass from the subjective panel was 95.4, 97.0 and 94.2 for the VBS2000, BCC2 and VIAScan, respectively, while fat class was lower at 74.6, 80.4 and 72.0%. SMY was predicted with an error reported as an RSD of 1.12-1.2% between the three systems (Allen, 2009). Craigie et al. (2012) calculated the median R^2 of the commercially available VIA systems according to the available data. The authors reported that for the prediction of saleable meat yield, fat percentage and bone percentage, the coefficients of determination were 0.70, 0.80 and 0.82, respectively. Irish abattoirs were the first to adopt automated grading by VIA in 2004 following calibration trials conducted under EU Regulations (EU 2017/1182, p.19) and many EU countries have since conducted their own authorisation trials. There have also been recent trials on the upgraded model of the Danish BCC-2, now known as the BCC-3, which is comprised of 8 pillars containing up to 40 cameras. The no-contact system can operate at a continuous line speed of 520 half carcasses/h. The system is currently installed in four European slaughter-plants and a South American plant while it undergoes assessment and calibration. A test on 86 carcass sides in a Danish plant demonstrated the ability of the system to predict the weight of the pistol cut, inside, knuckle and rump from veal with prediction errors of 0.910 kg, 0.280 kg, 0.191 kg and 0.162 kg, respectively (Esberg, Christensen, & Lauridsen, 2019).

Whole carcass VIA instruments have also been developed specifically for sheep carcasses. Rius-Vilarrasa, Bünger, Maltin, Matthews, and Roehe (2009) used the E+V VBS2000 to predict dissected primal meat yields obtaining R^2 from 0.86 to 0.97. Using VIAscan, Einarsson, Eythorsdottir, Smith, and Jonmundsson (2014) predicted lean meat yields in the leg, loin and shoulder with a R^2 =0.61, 0.31 and 0.47, respectively.

VIA systems are, therefore, useful tools to predict carcass conformation in a consistent way and can be successfully applied under harsh environments such as abattoirs. It can be installed in-line, speed is adequate for the meat industry requirements and it is non-intrusive such that measurements can be done without contact with the carcass. The main drawback is that the information provided only comes from the external (visible) surface of the carcass or side. This is important if carcass composition is to be estimated, as conformation and fat class are not considered good predictors of composition (Craigie et al., 2012) or intramuscular fat (Liu et al., 2020). Fat content is especially difficult for VIA, as it is the most variable component and is deposited in several locations in the carcass with the proportions in different locations being dependant on breed, sex, maturity and diet (Craigie et al., 2012) and due to VIA only determining the subcutaneous fat cover, it loses accuracy as the fat depth increases (Allen, 2009).

Incorporation of ‘time of flight’ (TOF) technology presents another opportunity to improve accuracy and resolution of the cameras of VIA systems. TOF provides 3D imaging using an infrared light source that illuminates the object and a detector receives the reflected light, so the depth information is added to the image. In all cases, a significant amount of research is required to prove the capabilities of the technologies. Nonetheless, TOF cameras have been proposed to be used as part of multi-sensor equipment (such as CT) to improve computer aided surgery (Pycinski, Czajkowska, Badura, Juszczyk, & Pietka, 2016) so their application could be emerging. In addition, as the technology field is fast evolving, and with that, the availability and cost of technologies is improving.

3.6. Optical and Spectroscopic Probes

In the 1980s several optical probes were developed based on the difference in reflectance of fat and muscle. The Fat-O-Meater (FOM) was created by researchers in the Danish Research Meat Institute and in New Zealand the Fat Depth Indicator, which later became the Hennessy Grading Probe (HGP) was developed. Both probes were originally designed for use on pig carcasses and are still used by the pig industry. In a recent conference, a new probe model based on fibre optical sensors and near infrared was tested on pig carcasses obtaining accurate predictions of lean meat ratio (Sun, Leng, Ma, Xu, & Xie, 2017). There is some research on the use of these probes on sheep carcasses (Hopkins et al., 2013), but as with all methods based on predicting carcass composition from subcutaneous fat depths, they are less accurate on beef and sheep than on pig carcasses for two main reasons. Firstly, the subcutaneous fat depot is a higher proportion of total carcass fat in pigs than in ruminants, so the part-whole relationship is weaker in the latter. Secondly, the subcutaneous fat layer is less even in ruminants, a situation that is made worse by hide removal, whereas the skin of pig carcasses is generally left on, preserving the more even layer. In the case of lamb carcasses, the generally lower fat depth range has been highlighted as a potential drawback for the use of these probes. However, Kongsro, Roe, Kvaal, Aastveit, and Egelandsdal (2009) observed high prediction accuracies using the HGP on lamb carcasses; fat and muscle weights were predicted with R^2=0.93 and 0.85, respectively. When compared to the GR knife, no improvements in accuracy were found (Siddell, McLeod, Toohey, van de Ven, & Hopkins, 2012) and it has also been reported that in the current state, the variation from the HGP is too high to be implemented in lamb abattoirs (Fowler et al., 2017).

In relation to meat quality, near-infrared (NIR) and Raman spectroscopy probes have been studied extensively. However, both spectroscopic techniques have shown high variability when predicting shear force, with R^2 values ranging from 0.01 to 0.74 (Berri et al., 2019). NIR spectroscopy has also been used as a research tool to predict sensory traits with better accuracy. Nonetheless, we cannot assert that the spectroscopic techniques are good predictors of sensory traits for several reasons: intensity scales used in sensory assessment are narrow and thus the accuracy is reduced, the samples tested with the probe will not be the same as the ones tested by the consumers, and the samples present a great amount of heterogeneity due to the nature of the muscle, animal maturity and breed (Berri et al., 2019). Combining spectroscopic and imaging techniques such as Hyperspectral or Multispectral Imaging (HSI or MSI respectively) offers promise (Jackman, Sun and Allen, 2011). These devices have the ability of generating an actual image with a spectral range for each of the pixels. Naganathan et al. (2016) have recently developed a prototype of HSI camera to be used on the ribeye surface of hanging carcasses in a commercial setup. The device was used on 274 beef carcasses and was able to predict shear force with an accuracy of 86.7% (using 101 carcasses for validation). In addition, other HSI and MSI devices such as MKII (Frontmatec) and Tenderspec are have been evaluated. The MKII was able to predict IMF from 400 lamb loins (24 h postmortem) with a root mean square error of 0.8% (Gardner, 2018). In a proof-of-concept study on the application of the Tenderspec to predict tenderness and IMF in Australian beef, 95% accuracy was achieved in identifying carcasses certified as tender. In addition, marbling scores derived from the US algorithms were more highly correlated to IMF than subjectively determined MSA marbling scores (Calkins, 2019). Therefore, hurdle technologies or advances in accuracy of technologies could lead to spectral techniques for prediction of eating quality attributes in an abattoir.

4. Future Directions

Technologies from other industries (e.g. medicine or aviation) are likely to lead to developments which could be applied within the meat industry. A small summary of the future directions for each of the non-invasive methods discussed in this review is presented in Figure 2. Apart from the advances already discussed in the previous sections, there are others that in the future could also generate an impact on the meat industry. An emerging biomedical imaging methodology based on the microwave spectrum and the dielectric properties of soft tissue is being developed; this technique is called microwave tomography (MWT) (Semenov, 2009). This technology, as opposed to x-ray based technologies and in line with NMR, uses non-ionizing radiation to obtain tomographic projection sets. MWT has the potential to be used in medical imaging for detection of different tissue malignancies (Semenov, 2009) but it has also been explored as an imaging technology for industrial processes (Wu & Wang, 2017). Golnabi, Meaney, and Paulsen (2016) studied the conjoint use of MRI and MWT to obtain increased accuracy in breast 3D images. This technology is still under development and with no real timing on when it would be available as a commercial medical device.

The University of Pennsylvania School of Veterinary Medicine in partnership with the imaging technology company 4DDI have developed a robotic CT scanner that collects a full 360 degrees of high-resolution medical images of live horses using two robotic arms (Hocter, 2016); this could overcome the issue of the restriction of carcass size especially for beef with current CT. In 2016, the company MB Telecom installed its first aircraft scanner which can scan an entire aircraft in about 6-8 minutes (Gillet, 2016). The x-ray scanner is mounted on a crane boom that beams a triangle of radiation down through the plane, while a robotic device pulls the aircraft through the scanning area and is able to scan objects as small as coins.

As the rate of technology advancement increases, there is great opportunity for the meat industry to evolve.

Objective carcass measurement, when performed accurately, could lead to more accurate payment systems for producers driving improvements in meeting market or consumer requirements. In addition, data collected could be used to inform other systems such as robotic sorting and cutting or traceability technologies, leading to overall improved process efficiencies. A recent study by Toohey, van de Ven, and Hopkins (2018), consulted with 65 red meat processors to gather their perspective on objective measurement and found that 88%

considered online measurement to have a role in the future. However, technology adoption will be case dependent as various factors play into the suitability of technologies per processor and factory and the grading methodology used in that country. Understanding the hurdles to technology adoption and variations between processors in the meat industry is therefore critical. If technologies are to be widely adopted as cited by Coleman (2013), who conducted interviews with 63 processors in Australia, new projects on OCM need to consider the cost of plant changes, the on-site expertise for operation and maintenance, workforce requirements in remote areas and the cost of training staff. Increased competitiveness amongst technology manufacturers could lead to capital cost reductions in future decades (Esberg et al., 2019) however, the pay-back benefit of additional prediction accuracy will also be a consideration.

5. Conclusions

Grading and classification systems vary between countries, with some based on yield or quality or both. A combination of both yield and quality measurement will most accurately describe the true value of the carcass, with objective systems offering potential to improve accuracy. In addition, systems may become more consistent globally with the establishment of international standards. Collaboration on a global scale, coupled with advancements in technology, could lead to genuine value based marketing systems where there are clear and transparent pricing signals between consumers and producers. By more accurately describing the carcass, selection for phenotypic traits and accurate payment systems will direct genotypic selection. The rate of technology advancement has increased as has the meat industry’s level of innovation and technology adoption. Several decades ago, VIA and optical probes were introduced into carcass evaluation systems. Whole carcass VIA offers a rapid, on-line and safe objective method for EUROP grading, LMY and SMY or hand-held VIA devices can be used for quality grading; however it is limited by only providing an external view of the carcass. In the last decade, DEXA was introduced for sheep and is currently being assessed for beef. The technique allows for rapid on-line prediction of LMY but is not suitable for every processor as it requires substantial space, investment and stringent safety protocols. In addition, it is commonly applied to the cold carcass, whereas other techniques like VIA, US and MI can be applied earlier in the process to the hot carcass. These challenges could be addressed as more companies innovate, such as those with equipment in the aviation sector, however they are not yet suited to the vertical line set-up of meat processing plants. Ultrasound and magnetic induction have been commercialised for LMY prediction in pigs. Ultrasound has been successful in predicting LMY in pigs and has been opted for by large processors with justified throughput, in favour of optical probes which still require manual operation. However, ultrasound accuracy is dependent on good contact with the animal, which limits its adoption in beef and sheep whose exterior is less smooth and prone to air bubbles which impede transmission. It will be interesting to see if recent innovations in magnetic induction can be translated to the beef and sheep sectors as this no-contact, continuous, vertical on-line technique has been shown to accurately predict LMY and primal weight in pigs.

The requirement to accurately describe the carcass in order to utilise other outcomes of Industry 4.0 such as robotics, IoT (internet of things), data traceability and increased competitiveness, may accelerate the adoption of objective carcass measurement in the future. Another driver will be accurately determining the eating quality of beef for improved consumer satisfaction and consistency in palatability in order to compete in a competitive protein market. This could see countries which currently do not grade for quality introduce additional grading steps. However, the ability of processors to avail of technologies to facilitate these changes will be case dependant.

Acknowledgements

This work was supported by Meat Technology Ireland (MTI) a co-funded industry/Enterprise Ireland Project (TC 2016 002).

References

Abdn, University of Aberdeen.(2017). Fast Field-Cycling MRI. Retrieved from https://www.identify-project.eu/

Abreu, L. R. A., Martins, P., Ribeiro, V. M. P., Gouveia, G. C., & Moraes, G. F. (2019). Genetic association between residual feed intake and carcass traits in a herd it of Nellore beef cattle. *Livestock Science, 225*, 53-61

Addis, A. H., Blair, H. T., Morris, S. T., Kenyon, P. R., & Schreurs, N. M. (2020). Prediction of the hind-leg muscles weight of yearling dairy-beef steers using carcass weight, wither height and ultrasound carcass measurements. *Animals, 10* (4), 651.

Allen, P. (2009). 20 - Automated grading of beef carcasses. In J. P. Kerry & D. Ledward (Eds.), *Improving the Sensory and Nutritional Quality of Fresh Meat* (pp. 479-492): Woodhead Publishing.

Allen, P., & Finnerty, N. (2000). *Objective beef carcass classification-A report of a trial of three VIA (video image analysis) classification systems*. Dublin: Teagasc and Department of Agriculture, Food and Rural Development.

Allen, P., & McGeehin, B. (2001). Measuring the content of carcasses using TOBEC. *The National Food Centre*.

Anderson, F., Cook, J., Williams, A., & Gardner, G. E. (2018). Computed tomography has improved precision for prediction of intramuscular fat percent in the M. longissimus thoracis et lumborum in cattle compared to manual grading. *Meat Science, 145*, 425-430

Aus-Meat (2018). Australian Beef Carcase Evaluation. Beef and Veal Chiller Assessment Language. WEB-024 / 2018. https://www.ausmeat.com.au/WebDocuments/Chiller_Assessment_Language.pdf

Baulain, U. (1997). Magnetic resonance imaging for the in vivo determination of body composition in animal science. *Computers and Electronics in Agriculture, 17*(2), 189-203

Bernau, M., Kremer, P. V., Lauterbach, E., Tholen, E., Petersen, B., Pappenberger, E., & Scholz, A. M. (2015). Evaluation of carcass composition of intact boars using linear measurements from performance testing, dissection, dual energy X-ray absorptiometry (DXA) and magnetic resonance imaging (MRI). *Meat Science, 104*(Supplement C), 58-66

Bernau, M., Schwanitz, S., Kremer-Rücker, P. V., Kreuzer, L. S., & Scholz, A. M. (2018). Size matters: Boar taint in relationship with body composition and testis volume measured by magnetic resonance imaging. *Livestock Science, 213*, 7-13

Berri, C., Picard, B., Lebret, B., Andueza, D., Lefevre, F., Le Bihan-Duval, E., Beauclercq, S., Chartrin, P., Vautier, A., Legrand, I., & Hocquette, J. F. (2019). Predicting the Quality of Meat: Myth or Reality? *Foods, 8*(10)

Bonny, S. P. F., O'Reilly, R. A., Pethick, D. W., Gardner, G. E., Hocquette, J.-F., & Pannier, L. (2018). Update of Meat Standards Australia and the cuts based grading scheme for beef and sheepmeat. Journal of Integrative Agriculture, 17(7), 1641-1654

Bosy-Westphal, A., & Muller, M. J. (2015). Assessment of fat and lean mass by quantitative magnetic resonance: a future technology of body composition research? *Curr Opin Clin Nutr Metab Care, 18*(5), 446-451

Calkins, C. R. (2019). An on-line system to assess beef quality characteristics: 2017-1070. Retrieved from https://www.ampc.com.au/2019/04/An-on-line-system-to-assess-beef-quality-characteristics

Carabus, A., Gispert, M., & Font-I-Furnols, M. (2016). Imaging technologies to study the composition of live pigs: A review. *Spanish Journal of Agricultural Research, 14*(3)

Carabus, A., Sainz, R. D., Oltjen, J. W., Gispert, M., & Font-i-Furnols, M. (2015). Predicting fat, lean and the weights of primal cuts for growing pigs of different genotypes and sexes using computed tomography. *Journal of Animal Science, 93,* 1388-1397

Cardoso, L. L., Tarouco, J. U., MacNeil, M. D., Lobato, J. F. P., Dambros, M. C., de Freitas, A. K., Devincenzi, T., Feijo, F. D., & Cardoso, F. F. (2020). Sample size and prediction of weight and yield of individual cuts from Braford steers pistol hindquarters. *Scientia Agricola, 77*(4), 8

Carometec.(2017).Autofom III. Retrieved October 2017 from http://www.carometec.com/products/item/autofom-lll

Castilhos, A. M., Francisco, C. L., Branco, R. H., Bonilha, S. F. M., Mercadante, M. E. Z., Meirelles, P. R. L., Pariz, C. M., & Jorge, A. M. (2018). In vivo ultrasound and biometric measurements predict the empty body chemical composition in Nellore cattle. *Journal of Animal Science, 96*(5), 1678-1687

Chay-Canul, A. J., Pineda-Rodriguez, J. J., Olivares-Perez, J., Rios-Rincon, F. G., Garcia-Herrera, R., Pineiro-Vazquez, A. T., & Casanova-Lugo, F. (2019). Prediction of carcass characteristics of discarded Pelibuey ewes by ultrasound measurements. *Revista Mexicana De Ciencias Pecuarias, 10*(2), 473-481

Choi, J. S., Kwon, K. M., Lee, Y. K., Joeng, J. U., Lee, K. O., Jin, S. K., Choi, Y. I., & Lee, J. J. (2018). Application of AutoFom III equipment for prediction of primal and commercial cut weight of Korean pig carcasses. *Asian-Australasian journal of animal sciences, 31*(10), 1670-1676

Clelland, N., Bunger, L., McLean, K. A., Knott, S., Matthews, K. R., & Lambe, N. R. (2018). Prediction of intramuscular fat content and shear force in Texel lamb loins using combinations of different X-ray computed tomography (CT) scanning techniques. *Meat Science, 140*, 78-85

Coleman, G. (2013). Issues relevant to the adoption of technology in the meat processing industry *Meat & Livestock Australia Limited.* A.TEC.0105. Retrieved from https://www.ampc.com.au/uploads/cgblog/id201/A.TEC.0105_Barriers_to_adoption_final_report.pdf

Connaughton, S. L., Williams, A., Anderson, F., Kelman, K. R., & Gardner, G. E. (2020). Dual energy x-ray absorptiometry precisely and accurately predicts lamb carcass composition at abattoir chain speed across a range of phenotypic and genotypic variables. A*nimal*, 1-9

Cook, J., & Anderson, F. (2017). Beef and Lamb OCM with CT in situ further development A.TEC.0123. Final Report. *Meat & Livestock Australia Limited*

Craigie, C. R., Navajas, E. A., Purchas, R. W., Maltin, C. A., Bunger, L., Hoskin, S. O., Ross, D. W., Morris, S. T., & Roehe, R. (2012). A review of the development and use of video image analysis (VIA) for beef carcass evaluation as an alternative to the current EUROP system and other subjective systems. *Meat Sci, 92*(4), 307-318

Daumas, G., Monziols, M., Rodriguez, J. M., Alvarez-García, & Causeur, J. D. (2019). *Estimation of the tissue composition of bellies by a magnetic induction scanner.* Paper presented at the 65th International Congress of Meat Science and Technology, Potsdam, Germany.

de Prados, M., Fulladosa, E., Gou, P., Munoz, I., Garcia-Perez, J. V., & Benedito, J. (2015). Non-destructive determination of fat content in green hams using ultrasound and X-rays. *Meat Sci, 104*, 37-43

DTI, Danish Technological Institute (2017).The world's first online CT scanner for food. Retrieved November 2019 from https://www.dti.dk/the-world-8217-s-first-online-ct-scanner-for-food/38790

Einarsson, E., Eythorsdottir, E., Smith, C. R., & Jonmundsson, J. V. (2014). The ability of video image analysis to predict lean meat yield and EUROP score of lamb carcasses. *Animal, 8*(7), 1170-1177

Ellis, K. J. (2001). Selected Body Composition Methods Can Be Used in Field Studies. *The Journal of Nutrition, 131*(5), 1589S-1595S

Esberg, J., Christensen, M., & Lauridsen, T. (2019). Final Report – Frontmatec BCC-3 beef classification system study and installation in Australia beef industry. *Meat & Livestock Australia Limited (MLA)*. P.PSH.0996.

Esquivelzeta, C., Casellas, J., Fina, M., Campo, M. D., & Piedrafita, J. (2017). Carcass traits and meat fatty acid composition in Mediterranean light lambs. *Canadian Journal of Animal Science, 97*(4), 734-741

Font-i-Furnols, M., Brun, A., & Gispert, M. (2019). Intramuscular fat content in different muscles, locations, weights and genotype-sexes and its prediction in live pigs with computed tomography. *Animal, 13*(3), 666-674

Font-I-Furnols, M., Brun, A., Marti, S., Realini, C. E., Perez-Juan, M., Gonzalez, J., & Devant, M. (2014). Composition and intramuscular fat estimation of Holstein bull and steer rib sections by using one or more computed tomography cross-sectional images. *Livestock Science, 170*, 210-218

Font-i-Furnols, M., Carabus, A., Pomar, C., & Gispert, M. (2015). Estimation of carcass composition and cut composition from computed tomography images of live growing pigs of different genotypes. *Animal, 9*(1), 166-178

Font-I-Furnols, M., Luo, X., Brun, A., Lizardo, R., Esteve-Garcia, E., Soler, J., & Gispert, M. (2020). Computed tomography evaluation of gilt growth performance and carcass quality under feeding restrictions and compensatory growth effects on the sensory quality of pork. *Livestock Science, 237*, 104023

Fornell, D.(2016).Recent Advances in MRI Technology. Retrieved October 2017 from https://www.itnonline.com/article/recent-advances-mri-technology

Fowler, S. M., Hoban, J. M., van de Ven, R., Boyce, M., Williams, A., Pethick, D. W., & Hopkins, D. L. (2017). A GR/Impedance probe proves unsuitable for measuring GR depth in Australian lamb carcases. *Meat Science, 129*, 71-73

Frisullo, P., Marino, R., Laverse, J., Albenzio, M., & Del Nobile, M. A. (2010). Assessment of intramuscular fat level and distribution in beef muscles using X-ray microcomputed tomography. *Meat Science, 85*(2), 250-255

Gardner, G., Presentation (2018).Objective carcase measurement. Transforming carcase grading. Retrieved from https://meetings.eaap.org/wp-content/uploads/2018/Session33/S33_09_Gardner.pdf

Gardner, G. E., Peterse, J., Starling, S. E., Cook, J., Shirazi, M., & Williams, A. (2017). Developing a dual X-ray absorptiometer for estimating carcass fatness in beef at abattoir chain-speed. *Proceedings of the 63rd International Congress of Meat Science & Technology (ICoMST). Cork, Ireland.*

Gardner, G. E., Starling, S., Brumby, O., Charnley, J., Glendenning, R., Coatsworth, R., Hocking-Edwards, J., Petersea, J., & A, W. (2016). DEXA Lamb Eating Quality and Supply Chain Grading A.MQA.0017. *Meat and Livestock Australia Limited*

Garza Hernandez et al. 2018. Analysis of single nucleotide polymorphisms variation associated with important economic and computed tomography measured traits in Texel sheep. Animal, 12(5), 915-922. doi: 10.1017/S1751731117002488.

Gillet, K.(2016).Romanian company takes aim at terrorism with world's first aircraft scanner. Retrieved October 2019 from http://www.easybib.com/reference/guide/apa/website

GMSteel. (2018). Automatic scanner for determining lean meat distribution in pig carcasses. EU Horizon FP7 Grant Number 719180. Retrieved from https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bcacdcec&appId=PPGMS

Golnabi, A. H., Meaney, P. M., & Paulsen, K. D. (2016). 3D microwave tomography of the breast using prior anatomical information. *Medical Physics*, *43*(4), 1933-1944

Ho, H., Yu, H. B., Gangsei, L. E., & Kongsro, J. (2019). A CT-image based pig atlas model and its potential applications in the meat industry. *Meat Science, 148*, 1-4

Hoban, J. M., Hopkins, D. L., Kirby, N., Collins, D., Dunshea, F. R., Kerr, M. G., Bailes, K., Cottrell, J. J., Holman, B. W. B., Brown, W., & Ponnampalam, E. N. (2016). Application of small angle X-ray scattering synchrotron technology for measuring ovine meat quality. *Meat Science, 117*(Supplement C), 122-129

Hocter, J.(2016).How robotic imaging for horses could offer breathing room for human CT scanning. Retrieved October 2019 from http://www.healthimaging.com/topics/diagnostic-imaging/robotic-imaging-horses-could-take-tube-out-human-ct-scanning

Hocquette J. & Ellies-Oury M. & Legrand I. & Pethick D. & Gardner G. & Wierzbicki J. & Polkinghorne R. J., (2020) “Research in Beef Tenderness and Palatability in the Era of Big Data”, *Meat and Muscle Biology* 4(2).

Hopkins, D. L., Toohey, E. S., Boyce, M., & de Ven, R. J. v. (2013). Evaluation of the Hennessy Grading Probe for use in lamb carcases. Meat Science, 93(3), 752-756

Jackman, P., Sun, D.-W., & Allen, P. (2011). Recent advances in the use of computer vision technology in the quality assessment of fresh meats. Trends in Food Science & Technology, 22(4), 185-197

Janiszewski, P., Borzuta, K., Lisiak, D., Grzeskowiak, E., & Stanislawski, D. (2019). Prediction of primal cuts by using an automatic ultrasonic device as a new method for estimating a pig-carcass slaughter and commercial value. *Animal Production Science, 59*(6), 1183-1189

Kipper, M., Pomar, C., Marcoux, M., & Radünz Neto, J. (2015). Evaluation of DXA technology to study the composition of pig carcasses and primal cuts. *Journées de la Recherche Porcine en France, 47*, 31-36

Kolstad K and Vangen O 1996. Breed differences in maintenance requirements of growing pigs when accounting for changes in body composition. Livestock Production Science 47, 23–32.

Kongsro, J., Roe, M., Kvaal, K., Aastveit, A. H., & Egelandsdal, B. (2009). Prediction of fat, muscle and value in Norwegian lamb carcasses using EUROP classification, carcass shape and length measurements, visible light reflectance and computer tomography (CT). *Meat Science, 81*(1), 102-107

Kremer, P. V., Fernandez-Figares, I., Forster, M., & Scholz, A. M. (2012). In vivo body composition in autochthonous and conventional pig breeding groups by dual-energy X-ray absorptiometry and magnetic resonance imaging under special consideration of Cerdo Iberico. *Animal, 6*(12), 2041-2047

Kuchida, K., Sakaguchi, Y., Kano, A., Goto, Y., & Komine, H. (2018). *Accuracy of measurement values from MIJ-camera system for beef grading of Japanese black* *in Japanese abattoir*. Paper presented at the 63rd International Congress of Meat Science and Technology, Melbourne, Australia.

Lambe, N. R., McLean, K. A., Gordon, A., Evans, D., Clelland, N., & Bunger, L. (2017). Prediction of intramuscular fat content using CT scanning of packaged lamb cuts and relationships with meat eating quality. *Meat Science*, *123*, 112-119

Langbridge, J. (2018). Training the E+V grading camera against Australian meat grading standards. *Meat & Livestock Australia Limited*. P.PIP.0751 Teys Australia Pty Ltd. . Retrieved from https://www.mla.com.au/download/finalreports?itemId=3760

Lee, S., Lohumi, S., Lim, H. S., Gotoh, T., Cho, B. K., & Jung, S. (2015). Determination of Intramuscular Fat Content in Beef using Magnetic Resonance Imaging. *Journal of the Faculty of Agriculture Kyushu University*, *60*(1), 157-162

Liu, J., Chriki, S., Ellies-Oury, M.-P., Legrand, I., Pogorzelski, G., Wierzbicki, J., Farmer, L., Troy, D., Polkinghorne, R., & Hocquette, J.-F. (2020). European conformation and fat scores of bovine carcasses are not good indicators of marbling. Meat Science, 170, 108233

López-Campos, O., Juárez, M., Larsen, I. L., Prieto, N., Roberts, J., Durgan, M. E. R., & Aalhus, J. L. (2017a). Dual energy x-ray absorptiometry as a rapid and non-destructive method for determination of lean, fat and bone content in livestock. *63rd ICoMST*

López-Campos, O., Larsen, I. L., Prieto, N., Juárez, M., Durgan, M. E. R., & Aalhus, J. L. (2017b). Evaluation of total lean and saleable meat yield prediction equations and dual energy x-ray absorptiometry for a rapid, non-invasive yield prediction in beef. *Meat Science*, *131*(Supplement C), 211

López-Campos, O., Larsen, I. L., Prieto, N., Juárez, M., Durgan, M. E. R., & Aalhus, J. L. (2017c). Using dual energy x-ray absorptiometry (DXA) for a rapid, non-invasive carcass fat and lean prediction in beef. *Meat Science*, *131*(Supplement C), 218

Losel, D., Kremer, P., Albrecht, E., & Scholz, A. M. (2010). Comparison of a GE Lunar DPX-IQ and a Norland XR-26 dual energy X-ray absorptiometry scanner for body composition measurements in pigs - in vivo. *Archiv Fur Tierzucht-Archives of Animal Breeding*, *53*(2), 162-175

Ludwiczak, A., Stanisz, M., Lisiak, D., Janiszewski, P., Bykowska, M., Skladanowska, J., & Slosarz, P. (2017). Novel ultrasound approach for measuring marbling in pork. *Meat Science*, *131*, 176-182

MacGhee, M. E., Bradley, J. S., McCoski, S. R., Reeg, A. M., Ealy, A. D., & Johnson, S. E. (2017). Plane of nutrition affects growth rate, organ size and skeletal muscle satellite cell activity in newborn calves. *Journal of Animal Physiology and Animal Nutrition*, *101*(3), 475-483

Massender, E., Brito, L. F., Canovas, A., Baes, C. F., Kennedy, D., & Schenkel, F. S. (2019). A genetic evaluation of growth, ultrasound, and carcass traits at alternative slaughter endpoints in crossbred heavy lambs. *Journal of Animal Science*, *97*(2), 521-535

Matika, O., Riggio, V., Anselme-Moizan, M., Law, A. S., Pong-Wong, R., Archibald, A. L., & Bishop, S. C. (2016). Genome-wide association reveals QTL for growth, bone and in vivo carcass traits as assessed by computed tomography in Scottish Blackface lambs. *Genetics Selection Evolution*, *48*

Mitchell, A. D., Ramsay, T. G., & Scholz, A. M. (2012). Measurements of changes in body composition of piglets from birth to 4 kg using quantitative magnetic resonance (QMR). *Archiv Fur Tierzucht-Archives of Animal Breeding*, *55*, 64-67

Mitchell, C. (2019). Carcass grading and payment systems to improve the eating quality of UK meat. *A Nuffield Farming Scholarships Trust Report*

MLA (2016). Meat Standards Australia. Standards Manual Section 8: Processor. Issue No. 4. https://www.mla.com.au/globalassets/mla-corporate/marketing-beef-and-lamb/documents/meat-standards-australia/section_8_processors_msa_standards_manual.pdf

Naganathan, G. K., Cluff, K., Samal, A., Calkins, C. R., Jones, D. D., Meyer, G. E., & Subbiah, J. (2016). Three dimensional chemometric analyses of hyperspectral images for beef tenderness forecasting. *Journal of Food Engineering, 169*, 309-320

Narsaiah, K., Biswas, A. K., & Mandal, P. K. (2020). Chapter 3 - Nondestructive methods for carcass and meat quality evaluation. In A. K. Biswas & P. K. Mandal (Eds.), Meat Quality Analysis (pp. 37-49): Academic Press.

Navajas, E. A., Richardson, R. I., Fisher, A. V., Hyslop, J. J., Ross, D. W., Prieto, N., Simm, G., & Roehe, R. (2010). Predicting beef carcass composition using tissue weights of a primal cut assessed by computed tomography. *Animal, 4*(11), 1810-1817

Olsen, E. V., Christensen, L. B., & Nielsen, D. B. (2017). A review of computed tomography and manual dissection for calibration of devices for pig carcass classification - Evaluation of uncertainty. *Meat Science, 123*, 35-44

Pannier, L., Gardner, G. E., O'Reilly, R. A., & Pethick, D. W. (2018). Factors affecting lamb eating quality and the potential for their integration into an MSA sheepmeat grading model. *Meat Sci, 144*, 43-52

Pereira, F. M. V., Pflanzer, S. B., Gomig, T., Gomes, C. L., de Felicio, P. E., & Colnago, L. A. (2013). Fast determination of beef quality parameters with time-domain nuclear magnetic resonance spectroscopy and chemometrics. *Talanta, 108*, 88-91

Pogorzelski, G., Woźniak, K., Polkinghorne, R., Półtorak, A., & Wierzbicka, A. (2020). Polish consumer categorisation of grilled beef at 6 mm and 25 mm thickness into quality grades, based on meat standards australia methodology. *Meat Science, 161*, 107953

Polkinghorne, R., Presentation.(2019).Path to implementation for eating quality grading. Retrieved from https://www.unece.org/fileadmin/DAM/trade/agr/meetings/ge.11/2019/MeatQuality_Aug2019/Pathway_to_Implementaton_-_Polkinghorne_Day2.pdf

Polkinghorne, R. J., & Thompson, J. M. (2010). Meat standards and grading: A world view. *Meat Science, 86*(1), 227-235

Pomar, C., Kipper, M., & Marcoux, M. (2017). Use of dual-energy x-ray absorptiometry in non-ruminant nutrition research. *Revista Brasileira De Zootecnia-Brazilian Journal of Animal Science, 46*(7), 621-629

Prados, L. F., Zanetti, D., Amaral, P. M., Mariz, L. D. S., Sathler, D. F. T., Valadares, S. C., Silva, F. F., Silva, B. C., Pacheco, M. C., Alhadas, H. M., & Chizzotti, M. L. (2016). Technical note: Prediction of chemical rib section composition by dual energy X-ray absorptiometry in Zebu beef cattle. *Journal of Animal Science, 94*(6), 2479-2484

Pycinski, B., Czajkowska, J., Badura, P., Juszczyk, J., & Pietka, E. (2016). Time-Of-Flight Camera, Optical Tracker and Computed Tomography in Pairwise Data Registration. *PLoS ONE, 11*(7), e0159493

Raza, S. H. A., Gui, L. S., Khan, R., Schreurs, N. M., Wang, X. Y., Wu, S., Mei, C. G., Wang, L., Ma, X. Y., Wei, D. W., Guo, H. F., Zhang, S., Wang, X. P., Kaleri, H. A., & Zan, L. S. (2018). Association between FASN gene polymorphisms ultrasound carcass traits and intramuscular fat in Qinchuan cattle. *Gene, 645*, 55-59

Rius-Vilarrasa, E., Bünger, L., Maltin, C., Matthews, K. R., & Roehe, R. (2009). Evaluation of Video Image Analysis (VIA) technology to predict meat yield of sheep carcasses on-line under UK abattoir conditions. *Meat Science, 82*(1), 94-100

Sarubbi, F., Baculo, R., & Balzarano, D. (2008). Bioelectrical impedance analysis for the prediction of fat-free mass in buffalo calf. *Animal, 2*(9), 1340-1345

Scholz, A. M., Bunger, L., Kongsro, J., Baulain, U., & Mitchell, A. D. (2015). Non-invasive methods for the determination of body and carcass composition in livestock: dual-energy X-ray absorptiometry, computed tomography, magnetic resonance imaging and ultrasound: invited review. *Animal, 9*(7), 1250-1264

Scholz, A. M., Kremer-Rücker, P., Wenczel, R., Pappenberger, E., & Bernau, M. (2013). Body composition in farm animals by dual energy X-ray absorptiometry. In C. Maltin, C. Craigie & L. Bunger (Eds.), *Farm animal imaging Dublin 2012* (pp. 9-15). Ingliston (UK): Quality Meat Scotland.

Schulz, L., & Sundrum, A. (2019). Assessing marbling scores of beef at the 10th rib vs. 12th rib of longissimus thoracis in the slaughter line using camera grading technology in Germany. *Meat Sci, 152*, 116-120

Seaton, M. (2017). LEAP 4 Beef – Vision development and preliminary concepts P.PSH.0741. *Meat & Livestock Australia Limited*

Semenov, S. (2009). Microwave tomography: review of the progress towards clinical applications. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences, 367*(1900), 3021-3042

Siddell, J., McLeod, B. M., Toohey, E. S., van de Ven, R., & Hopkins, D. L. (2012). The prediction of meat yield in lamb carcasses using primal cut weights, carcass measures and the Hennessy Grading Probe. *Animal Production Science, 52*(6-7), 584-590

Silva, S. R. (2017). Use of ultrasonographic examination for *in vivo* evaluation of body composition and for prediction of carcass quality of sheep. *Small Ruminant Research, 152*, 144-157

Silva, S. R., Afonso, J., Monteiro, A., Morais, R., Cabo, A., Batista, A. C., Guedes, C. M., & Teixeira, A. (2018). Application of bioelectrical impedance analysis in prediction of light kid carcass and muscle chemical composition. *Animal, 12*(6), 1324-1330

Simeonova, M. L., Todorov, N. A., & Schinckel, A. P. (2012). Review of in vivo methods for quantitative measurement of protein deposition rate in animals with emphasize on swine. *Bulgarian Journal of Agricultural Science, 18*(4), 455-481

Simoncini, N., Virgili, R., Schivazappa, C., Pinna, A., Rossi, A., Alvarez, J., & Rodríguez, J. M. (2012). *Assessment of fat and lean content in Italian heavy green hams by means of on-line non-invasive techniques.* Paper presented at the 58th International Congress of Meat Science and Technology, Montreal, Canadá.

Su, H., Golden, B., Hyde, L., Sanders, S., & Garrick, D. (2017). Genetic parameters for carcass and ultrasound traits in Hereford and admixed Simmental beef cattle: Accuracy of evaluating carcass traits. *Journal of Animal Science, 95*(11), 4718-4727

Sun, Z. C., Leng, S., Ma, W. T., Xu, Q., & Xie, X. M. (2017). Method for Detection of the Lean Meat Ratio in Pork Carcass Based on Fiber Optic Sensor. In H. L. Yuan, R. K. Agarwal, P. Tandon & E. X. Wang (Eds.), *2016 the 3rd International Conference on Mechatronics and Mechanical Engineering* (Vol. 95).

Toohey, E. S., van de Ven, R., & Hopkins, D. L. (2018). The value of objective online measurement technology: Australian red meat processor perspective.J Animal Production Science. *58*(8), 1559-1565

Webster, B. (2019). Evaluation of eating quality attributes measured by TD-NMR. *Meat & Livestock Australia Limited (MLA)*. P.PSH.0878.

Williams, A., Anderson, F., Siddell, J., Pethick, D. W., Hocking-Edwards, J. E., & Gardner, G. E. (2017). Carcase grading – accurate determination of lean meat yield and its value to industry. *Proceedings of the 63rd International Congress of Meat Science & Technology (ICoMST). Cork, Ireland.*

Willner, M., Viermetz, M., Marschner, M., Scherer, K., Braun, C., Fingerle, A., Noel, P., Rummeny, E., Pfeiffer, F., & Herzen, J. (2016). Quantitative Three-Dimensional Imaging of Lipid, Protein, and Water Contents via X-Ray Phase-Contrast Tomography. *Plos One*, *11*(3)

Woerner, D. R., & Belk, K. E. (2008). The history of instrument assessment of beef. Retrieved 7 August 2020 from https://www.beefresearch.org/CMDocs/BeefResearch/The%20History%20of%20Instrument%20Assessment%20of%20Beef.pdf

Wu, Z. P., & Wang, H. G. (2017). Microwave Tomography for Industrial Process Imaging. *Ieee Antennas and Propagation Magazine*, *59*(4), 61-71

Appendix

Relevant Legislation and Regulations

Commission regulation (EC) No 1249/2008 of 10 December 2008 laying down detailed rules on the implementation of the Community scales for the classification of beef, pig and sheep carcases and the reporting of prices thereof. Retrieved 10 Jan 2019 https://eur-lex.europa.eu/eli/reg/2008/1249/oj

Commission Delegated Regulation (EU) 2017/1182 of 20 April 2017 supplementing Regulation (EU) No 1308/2013 of the European Parliament and of the Council as regards the Union scales for the classification of beef, pig and sheep carcasses and as regards the reporting of market prices of certain categories of carcasses and live animals. Retrieved 31 March 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1585621409583&uri=CELEX:32017R1182

Council Regulation (EEC)No 1208/81 of 28 April 1981 determining the Community scale for the classification of carcases of adult bovine animals. Accessed 31 March 2020 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1981R1208:19910429:EN:PDF

Commission Regulation (EEC) No 2930/81 of 12 October 1981 adopting additional provisions for the application of the Community scale for the classification of carcases of adult bovine animals. Accessed 31 March 2020 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1981R2930:19910730:EN:PDF

Tables

Table 1. Characteristics of carcass classification and grading schemes from main livestock producers and exporters

Country	**Australia**		**Brazil**	**Canada**	**Europe**	**Japan**	**South Africa**	**USA**
Scheme	**AUS-MEAT**	**MSA**	**-**	**Canada**	**EUROP**	**JMGA**		**USDA**
Beef	Carcass weight Sex Dentition Grain fed Optional: Maturity Meat colour Fat colour Marbling Fat thickness Eye muscle area	Cut-based Quality Carcass weight Sex Tropical breed Hanging method HGP Ossification Marbling Rib fat thickness pH Hump height Meat colour* Ageing time Cooking method	Carcass weight Sex Dentition Fat cover	Sex Quality Conformation Maturity Colour muscle Colour fat covering Yield and marbling on 12th rib Carcass weight Ribeye area Fat thickness Intramuscular fat	Animal Type Carcass weight Sex Conformation Fat cover	Sex Quality Marbling Colour and brightness muscle Firmness and texture Fat colour and lustre Yield Left side weight On 6th rib: Ribeye area Rib thickness Fat thickness	Carcass weight Sex Dentition Conformation Fat cover	Sex Quality (12th rib) Marbling Maturity Firmness Yield Carcass weight Kidney, pelvic and heart fat External fat Ribeye area
Sheep	Carcass weight Sex Dentition Fat class Depth at GR	Carcass weight Dentition Fat class Depth at GR Hanging method pH Ageing	-	Carcass weight Age Sex Quality Maturity Fat thickness Muscling Fat cover	Carcass weight Age Conformation Fat cover	-	Carcass weight Sex Dentition Conformation Fat cover	Quality+Yield Flank fat streakings Maturity Conformation

		Cooking method		colour Flank muscles colour Yield Fat thickness at 12th rib				
Pig	Carcass weight Sex Fat thickness at P2	-	Not official Own industry classifications Carcass weight Fat thickness	Lean Yield Carcass Weight Fat depth	Carcass weight Lean meat content	Sex Primary grade Carcass weight Backfat thickness Secondary grade Drip Texture Meat colour Fat colour Marbling	Sex Classes Carcass weight Meat percentage Fat thickness	Sex Carcass weight Backfat thickness Muscling

*MSA measured but removed from EQ prediction (MLA, 2016)

Table 2. Recent research on the application of CT to carcass characteristics and quality traits

Objective	**Application**	**Results**	**Reference**
Composition	In vivo lambs	R^2=0.92, 0.74 and 0.85 for fat, bone and muscle weight, respectively	Matika et al., 2016
Measurement of IMF	In vivo lambs and pigs	Regression coefficient of 0.51-0.71 (lambs) and 0.18 (pigs)	Clelland et al., 2018; Kongsro & Gjerlaug-Enger, 2013
Carcass composition	Heifers and Steers	R^2=0.97 for meat, fat and bone	Navajas et al., 2010
Meat content compared to EUROP	Suckling bulls	A better predictor of the meat content than the EUROP classification in suckling bulls (r=0.7 vs. r=0.55)	Holló, Barna, & Nuernberg, 2014
Cut weight and fat	Holstein bulls and steers rib section	R_P^2 of 0.88 and 0.98 for cut weight and fat, respectively R_P^2=0.60 for IMF	Font-I-Furnols et al., 2014
IMF	Pigs	R_P^2=0.17 (all muscles), R_P^2=0.42 (sirloin), R_P^2=0.07 (ham)	Font-I-Furnols et al., 2019
IMF	Lambs	Good correlation (r=0.71) IMF v Soxhlet	Anton, Zsolnai, Hollo, Repa, and Hollo, 2013
IMF	Lamb cuts	IMF prediction reached only moderate values (R^2=0.36)	Lambe et al., 2017

Table 3. Recent research on the application of ultrasound (US) on live animals and carcasses

Objective	Animal	Results	Reference
High value cuts weight	Bradford steers	R^2 =0.36 (striploin weight)	Cardoso et al., 2020
Genetic evaluation of Ultrasound measured traits	Nellore beef	Ribeye area, backfat thickness and rump cap fat measured with US have potential for genetic improvement	Abreu et al., 2019
Carcass and muscle weight	Pelibuey ewes	R^2 =0.51-0.66 (carcass weight), R^2 =0.44-0.57 (muscle weight)	Chay-Canul et al. 2019
Yield of valuable cuts	Pig carcasses	R^2 =0.98 (belly muscle thickness), R^2 =0.93 (loin %)	Janiszewski et al., 2019
Hot carcass weight and GR fat depth	Crossbred lambs	R =0.33-0.71 (hot carcass weight), R=0.38-0.74 (fat depth GR)	Massender et al. 2019
Yield grades	Angus steers	Higher Ribeye Area lower yield grades	Armstrong et al., 2018
Chemical composition of carcass	Nellore beef	R^2 =0.94 (protein)[a], R^2=0.74 (fat)[b], R^2=0.96 (water)[b]	Castilhos et al., 2018
Fatty acid synthase gene polymorphisms	Qinchuan cattle	Two SNPs associated with US carcass traits	Raza et al., 2018
Carcass characterisation	Mediterranean light lambs	US measurements used for characterisation	Esquivelzeta et al., 2017
Marbling	Pig carcasses	R=0.811 (IMF from inside carcass US)	Ludwiczak et al., 2017
Carcass merit	Hereford and Simmental cattle	Only in Hereford cattle US measurements more reliable than manual measurements (Fat thickness, longissumus muscle area and marbling score).	Su et al., 2017
IMF	Pigs	R^2 up to 0.92	Carabus et al., 2016

[a] US rump fat thickness in addition to shrunk body weight and hip height, [b] US rump fat thickness in addition to shrunk body weight and age

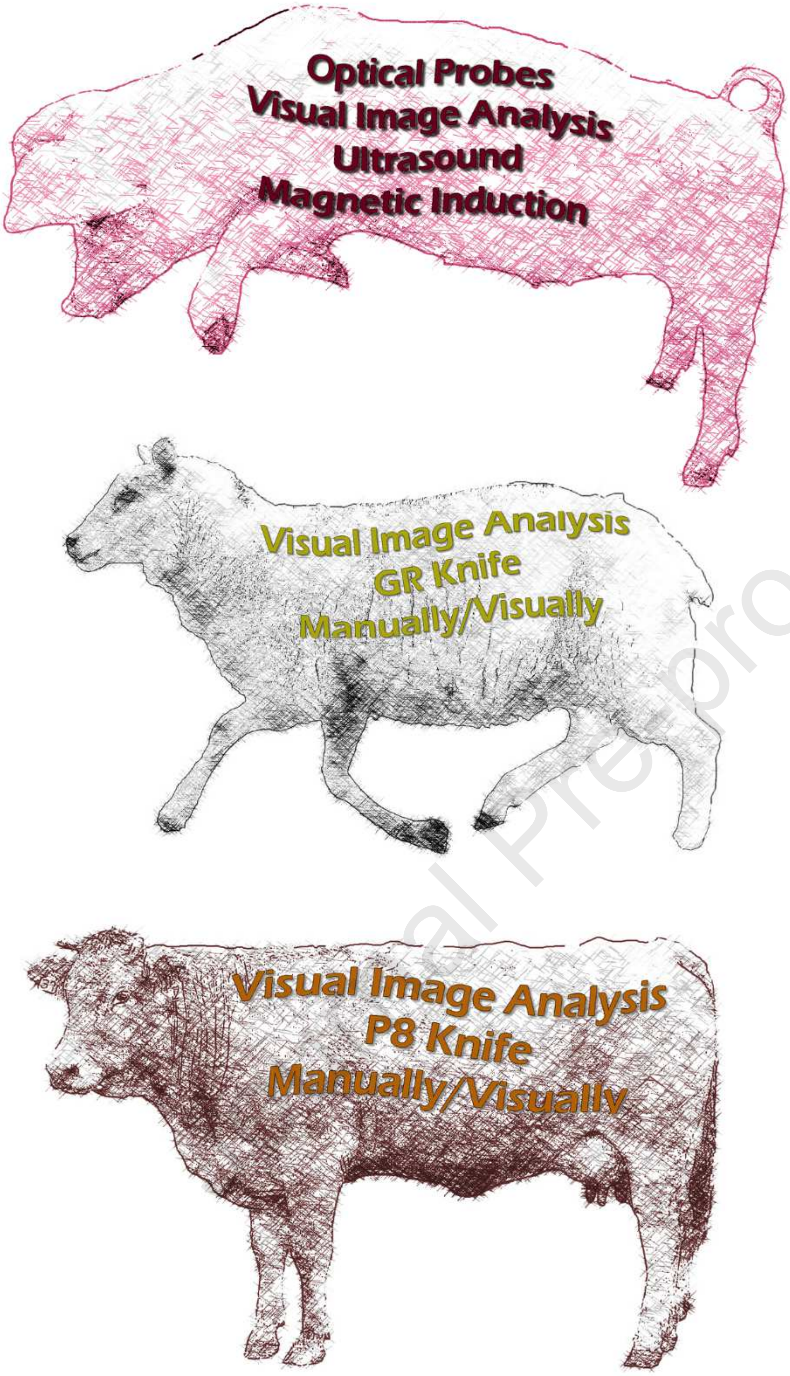

Figure 1. Current commercialised technologies for grading pigs, sheep and cattle carcasses

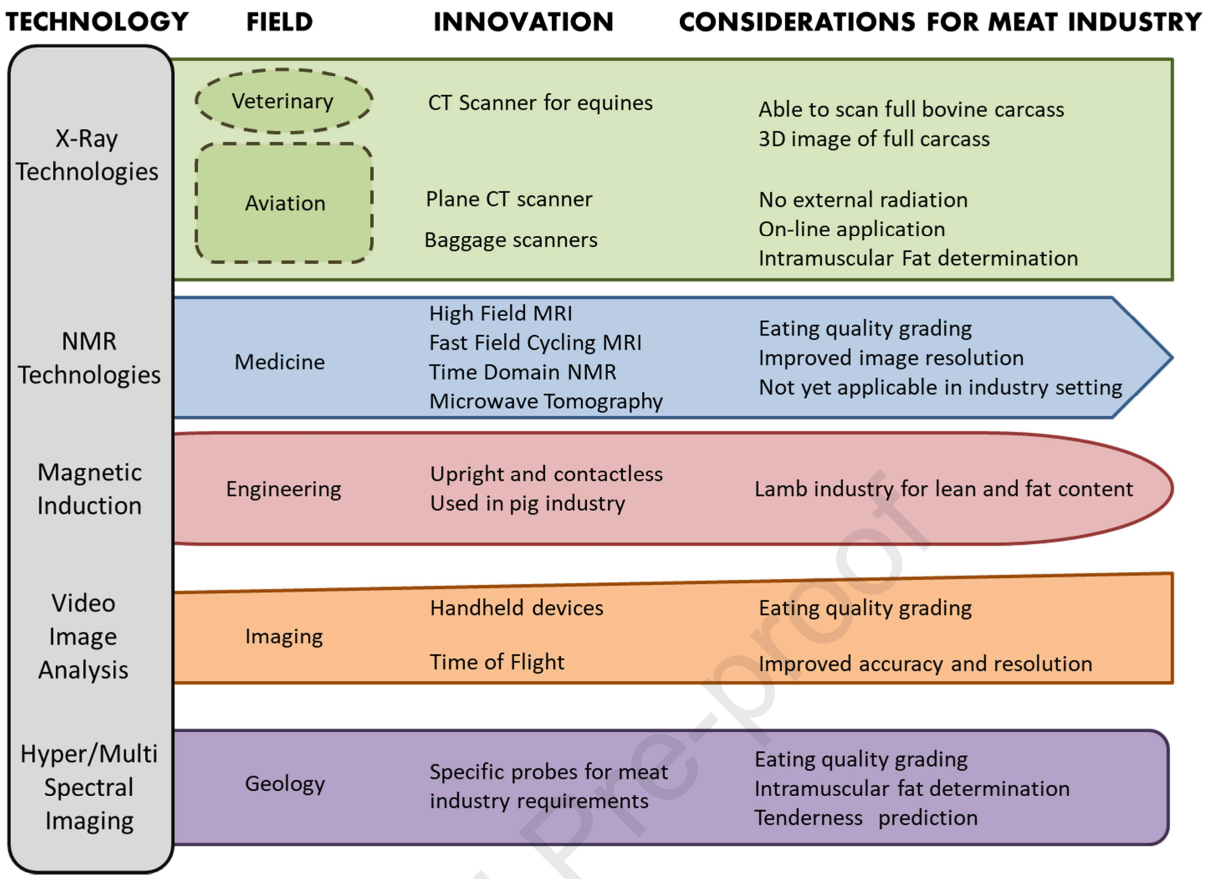

Figure 2. Future directions of objective carcass measurement technologies

Highlights:

- ~~Grading for both eating quality and yield can lead to improved value based systems~~
- ~~Global grading systems differ but international standards for EQ grading exist~~
- ~~CT remains the gold standard for lean meat yield~~
- ~~Recent commercialised updates of VIA, DEXA and magnetic induction exist~~

- A summary of global beef, sheep and pig grading practices is provided
- International standards for beef grading could lead to improved eating quality
- Grading for both eating quality and yield can lead to improved value based systems
- Recent commercial advances in VIA, DEXA and magnetic induction are discussed
- Perspectives on future directions for objective carcass measurement are provided