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A method for nondestructive prediction of pork meat quality and safety attributes by hyperspectral imaging technique

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ABSTRACT

Rapid and nondestructive methods for predicting meat quality and safety attributes are of great concerns at present. A Hyperspectral imaging technique was investigated for evaluating pork meat tenderness and *Escherichia coli* (*E. coli*) contamination in this study. Totally 31 samples were used for hyperspectral imaging in the spectral range of 400–1100 nm. A novel method by Modified Gompertz function was exploited to extract the scattering characteristics of pork meat from the spatially-resolved hyperspectral images. Gompertz parameters α, β, ε and δ which can represent different optical meanings were derived by curve-fitting to the original scattering profiles. The fitting coefficients were all around 0.99 between 470 and 960 nm, which indicating the effective interpretation by Gompertz function. Multi-linear regression models were established using both individual parameters and integrated parameters, and the results showed that Gompertz parameter δ was superior to other individual parameters for both pork meat tenderness and *E. coli* contamination, and the integrated parameter can perform better than individual parameters. The validation results (R_{CV}) by the integrated parameter method were 0.949 and 0.939 for pork meat tenderness and *E. coli* contamination respectively. The study demonstrated that hyperspectral imaging technique combined with Gompertz function was potential for rapid determination of pork meat tenderness and *E. coli* contamination, and so hopefully to provide a promising tool for monitoring the multiple attributes concerning meat quality and safety.

1. Introduction

With the development of economy and improvement of people's living standards, meat and meat products have become an important food item in the human diet. According to the report, over the past 50 years, the global meat consumption has quadrupled from 70 million tons in 1961 to a current total of 283 million tons in 2011 (According to Global agricultural). It is well known that pork meat is one of the most important meat products in people's food. In 2011, the global production of pork meat was around 101 million tons, which accounted for 34% of the total meat production. However, the great expansion of meat industry and increasing demand of consumers for high-quality and safe meat have also produced new challenges for the meat industry.

One challenge facing meat industries is to obtain reliable information on meat quality throughout the production process, which would ultimately provide a guaranteed quality of meat products for consumers. The meat producers may incur economic losses if meat quality is not judged accurately for marketing, as the great variability in raw meat leads to highly variable products being marketed without a controlled level of quality (Damez and Clerjon, 2008; Xing et al., 2007). This problem will be aggravated when the industry is unable to satisfactorily characterize this level of quality and cannot therefore market products with a certified quality level, which is an otherwise essential condition for the survival and development of any modern industry. Among conventional quality attributes such as meat color, tenderness, juiciness and water holding capacity, consumer research suggests that tenderness is the most important element for eating quality and the variation in meat tenderness will directly affect consumers' decision to repurchase (Boleman, 1995; Fonseca et al., 2003). At present, the determination of meat tenderness is mainly via shear force apparatus or sensory assessment in meat industries. However, these methods are time-consuming, destructive, and are not suitable to fast-paced production or processing environment in meat plants (Xing et al., 2007). It is reported that the lack of fast, reliable and nondestructive methods for determining meat characteristics has been one of the main obstacles for the development of quality control in the meat industry (ElMasry et al., 2011b). Therefore, an effective technique that can rapidly and nondestructively segregate meat carcasses or cuts based on predicted tenderness is highly desirable for meat producers.

The widespread and increasing incidences of food-borne diseases have brought meat safety to the forefront of public health

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concerns, and microbial hazard was reported to be one of the major challenges to meat safety (Sofos, 2008). Nowadays, one of the tools to ensure meat safety in meat plants is to implement Hazard Analysis and Critical Control Point (HACCP) (Vanne et al., 1996). The HACCP plans in meat plants mainly focus on control measures that can reduce the likelihood of contamination of meat from microbial hazards. Whereas, conventional methods for bacteria detection are labor-intensive, requiring cumbersome pretreatments and long time for bacteria incubation, and thus it is difficult to give timely and effective control on contaminated meat when applying HACCP plans (Ellis and Goodacre, 2001; Ellis et al., 2002, 2005). Therefore, advanced sensing technologies that can nondestructively inspect bacteria contamination would greatly reduce the risk of unsafe meat, and meanwhile the application of HACCP plans in meat plants further advances the need for rapid and nondestructive methods in microbiology.

Among current emerging technologies, optic-based methods were reported to have the greatest potential for online application (Shackelford et al., 1999; Vote et al., 2003). Therefore, use of optical methods has been extensively studied and implemented as an alternative to conventional analytical methods which are destructive and time-consuming. The Near infrared spectroscopy (NIR) has been investigated to predict beef tenderness, while the correlation coefficient (R) yielded only reached to 0.61–0.81 (Park et al., 1998; Rødbotten et al., 2000; Zhao et al., 2006). Moreover, considerable inconsistency among the samples of different genders and post-slaughter time was also reported for the prediction of beef tenderness using NIR technology (Rødbotten et al., 2000). Recently, NIR spectroscopy has also been applied to evaluate the bacterial contamination in shredded cabbage (Suthiluk et al., 2008), and detection and discrimination of *Escherichia coli* (*E. coli*) ATCC 25922 and *E. coli* K12 (Siripatrawan et al., 2010). However, conventional NIR spectroscopic instruments are commonly considered as point-based scanning instruments, and thus spectra obtained from NIR instruments do not give the spatial information of a sample (Gowen et al., 2008, 2009).

Hyperspectral imaging technique is a new rapidly growing technique which integrates spectroscopic and imaging techniques in one system for providing both spectral and spatial information simultaneously. As a result, each hyperspectral image contains a large amount of information in a three-dimensional (3-D) form called "hypercube" which can be analyzed to characterize the object more reliably than the traditional machine vision (Kumar and Mittal, 2010) or spectroscopy techniques (Klaypradit et al., 2011; Quevedo and Aguilera, 2010). Hyperspectral imaging was originally developed for remote sensing (Goetz et al., 1985), and has currently emerged as a powerful tool for nondestructive assessment of agro-products' quality and safety (Gowen et al., 2007). Considerable research studies have been reported on applying hyperspectral imaging technique to determine the inner quality of fruits (Lu and Peng, 2006; Mendoza et al., 2011; Peng and Lu, 2008), detect apple surface defects/contamination (Kim et al., 2002; Liu et al., 2007; Mehl et al., 2004), identify poultry contaminants (Lawrence et al., 2006; Park et al., 2002, 2006; Yoon et al., 2011), evaluate meat quality (ElMasry et al., 2011a; Liu et al., 2010; Qiao et al., 2007; Wu et al., 2012) and detect the bacterial contamination of meat and vegetables (Barbin et al., 2013; Feng et al., 2013; Peng et al., 2010, 2011; Siripatrawan et al., 2011; Tao et al., 2010, 2012a), etc.

Meat is known to be a turbid biological material, which indicating that the interaction with light involves both absorption and high scattering, and thus the resulting light attenuation can no longer be adequately described by the Beer–Lambert law (Qin and Lu, 2008; Tao et al., 2012b). The advantage of hyperspectral imaging is to provide the spatial information simultaneously besides providing the spectral information for each pixel in the image, and therefore one approach that can analyze the hyperspectral data based on both spectral and spatial information would definitely represent the sample better. Previous studies have reported the usefulness of spatially-resolved hyperspectral images (hyperspectral scattering method) for evaluating the quality attributes of fruits, meat and milk (Peng and Lu, 2007, 2008; Peng et al., 2010, 2011; Qin and Lu, 2007; Tao et al., 2012a; Wu et al., 2012). The hyperspectral scattering method is based on the hardware system in which the point light was applied as the illuminant source, and thus the scattering pattern of the object can be acquired by resolving the hyperspectral image spatially. Whereas, the reports on comprehensively evaluating meat quality and safety attributes by this method are still rare.

In the previous study, we have investigated using the spatially-resolved hyperspectral images which were analyzed by the 3-parameter Lorentzian function to predict pork meat tenderness and *E. coli* contamination and reported the potential of hyperspectral scattering method for the nondestructive evaluation of meat quality and safety attributes (Tao et al., 2012a). Lorentzian function is commonly used to describe the laser profiles and light distribution patterns in optics research (Davis, 1996). While, Gompertz function curves were reported to have a steeper gradient than Lorentzian function curves near the saturation area which implies that Gompertz function would be a more effective function to fit the scattering profiles with the steep descending gradient nearby the saturation area (Peng and Lu, 2007). Therefore, compared to our previous study, the objectives of this article are to present a more effective data analysis method for spatially-resolving hyperspectral images by Gompertz function, validate its usefulness on nondestructive determination of the multiple attributes of pork meat (taking tenderness and *E. coli* contamination as an example in the article) and also compare these results to the ones that analyzed by 3-parameter Lorentzian function. One promising tool for comprehensively monitoring the multiple attributes of meat quality and safety was provided in the article.

2. Materials and methods

2.1. Hyperspectral imaging system

A hyperspectral imaging system in the spectral range of 400–1100 nm was used to acquire the images of pork meat samples. Fig. 1 shows the sketch of hyperspectral imaging system used in this study. The hyperspectral imaging system mainly consisted of a high-performance back-illuminated 12-bit charge coupled device (CCD) camera (Sensicam QE, PCO AG, Kelheim, Germany), an imaging spectrograph (ImSpector V10E, Spectral Imaging Ltd., Oulu, Finland), an illumination unit (Oriel Instruments, Stratford, USA) equipped with optical fiber, a computer supported with a data acquisition and control software (Camera control Kit V2.19, the Cooke Corp., Germany). The optical fiber was used to form point light in the imaging system, and the diameter of the light beam formed was 5 mm, with working power in 150 W and incidence angle around 15°. The system worked in a line scanning mode, and all scans were obtained at a position of 3 mm (from the incident light center to the scanned position) off the incident light center in order to avoid the signal saturation on CCD detector.

The resolution of the imaging system was spectrally 2.8 nm with a 0.74 nm interval, and spatially less than 9 μm. The image generated by this system was of 1376 × 1040 (spatial × spectral) pixels, with the binning in the horizontal and vertical directions of 1, 2, 4, 8 and 1, 2, 4, 8, 16 respectively. Additionally, in order to minimize the effect of ambient light, the imaging system was enclosed in a shield box.