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Development of an alternative technique for rapid and accurate determination of fish caloric density based on hyperspectral imaging

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ABSTRACT

This study aimed to develop an alternative technique for rapid, accurate and non-invasive determination of gross energy density values of salmon fillets based on hyperspectral imaging (900–1700 nm). Spectral data were extracted from the hyperspectral images with outlier pixels removed. Good performances were achieved with r_P of 0.906 and 0.909, and normalized RMSEP of 6.768% and 7.064% for partial least squares regression (PLSR) and epsilon-support vector regression (epsilon-SVR) analysis, respectively. The optimized stepwise-PLS model built with four wavelengths (931, 1001, 1135 and 1168 nm) yielded good results with r_P of 0.908 and normalized RMSEP of 6.871%. The distribution maps for visualizing energy density indices in all portions of the salmon fillet were subsequently generated. The overall results confirmed the successful development of a rapid and non-destructive technique using hyperspectral imaging for determining energy value of salmon fillets, and the provision of an alternative method for caloric density measurement for the food industry.

1. Introduction

With the increasing awareness from consumers on food and health, the food industry not only requires techniques such as drying (Cui et al., 2008; Sun and Woods, 1994), cooling (McDonald and Sun, 2001; Sun, 1997; Wang and Sun, 2004; Zheng and Sun, 2004) and freezing (Kiani et al., 2011) to maintain the food quality, it also requires novel and rapid methods to determine the food nutritional values. Especially in recent years, the global prevalence of overweight and obesity has remarkably increased, for example, in 1980 approximately 29% of adults were overweight or obese, which was increased to 38% in 2013 (Crino et al., 2015). Obesity and overweight are major health concerns, given the association with chronic conditions including diabetes, stroke, hypertension, hypercholesterolemia, heart disease, certain cancers, and arthritis. Although obesity or overweight is a multifactorial disease, an energy imbalance in intake and expenditure is commonly believed as its main cause. In this regard, nutrition labelling of foods sold in stores and restaurants is designed to provide the public with calorie information to make informed choices about food purchases. This has been considered to be an attractive and potentially effective policy as the knowledge about the calorie content of foods will motivate and/or guide individuals to consume the appropriate amount of calories for proper weight management. Many consumer research studies have reported the importance of food calorie information displayed on front-of-pack nutrition labels and its effect on food choices of consumers (Fernandes et al., 2015). However, achieving optimal energy intake goals through self-monitoring relies on the accuracy of energy information available for consumed foods. Inaccuracies in reported food energy content, if replicated, could lead to either inadvertent overeating or undereating and hamper efforts to use self-monitoring for weight control.

The early method used to calculate the calorie counts in a given food directly measures the energy produced. The food source is placed in a sealed container filled with water - an apparatus known as a bomb calorimeter. After the food is completely burned, the resulting rise in water temperature is measured. Currently the Atwater system based on an indirect calorie estimation, developed by the U.S. chemist Wilbur Olin Atwater more than 100 years ago (Maynard, 1944), is widely used to determine caloric values in the industry food tables, in part because of its obvious simplicity. Instead of calculating calories directly by burning the foods, this approach adds up the calories provided by the energy-containing

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nutrients: protein, carbohydrate, fat and alcohol. The Atwater system uses the general factors of 4 kcal/g for protein, 4 kcal/g for carbohydrate, 9 kcal/g for fat and 7 kcal/g for alcohol (Rumpler et al., 1996). It is worth noting that these numbers were originally determined by burning and then averaging. Over the past years, the limitations and misuses of the general calories factors, have been pointed out when applied to individual foods and different types of diets (Acheson et al., 1980; Buchholz and Schoeller, 2004). There is no doubt that the general factors are far inferior to the food-specific Atwater factors, but both general and specific food energy factors are under strain: the specific factor system due to its complexity (different factors being used for different foods) and the general factor system due to inaccuracies compared to the specific factors (Livesey, 2001). Although the calorie calculation approach is simple and straightforward, the process to determine the content of energy-containing nutrients, including protein, carbohydrate and fat are destructive, time-consuming and laborious. More importantly, different food products from the same batch vary in their exact content. Hence, using a single test at this point in time for approximation might not work on different food products in the future. Therefore, development of a rapid, non-destructive and real-time alternative technique with higher accuracy is highly valuable for the food industry.

To date, visible and near-infrared (NIR) hyperspectral imaging (HSI) as a smart and promising analytical tool has been proven to be a versatile and useful technique in food quality analysis and control (Cheng and Sun, 2015; Lorente et al., 2012; ElMasry et al., 2012a; Barbin et al., 2012; ElMasry et al., 2012b; Feng and Sun, 2012; Wu and Sun, 2013b; Barbin et al., 2013; Kamruzzaman et al., 2013; Feng and Sun, 2013; Feng et al., 2013).NIR HSI is an integrated technique of spectroscopy and imaging or computer vision (Wu and Sun, 2013c; Wang and Sun, 2002; Jackman et al., 2009), and thus has the advantage of providing both spatial and spectral information of a food item. In terms of the applications in fish, HSI technique has been successfully used for measurement of protein in fishmeal (Masoum et al., 2012), determination of fat, moisture, and sodium in cured salmon (Huang et al., 2003), detection of nematode in cod fillets (Sivertsen et al., 2011) and evaluation of microbial spoilage in salmon flesh (Wu and Sun, 2013a). As mentioned above, protein and fat in the meat contributed most to the energy value when consumed. Lipid contents are considerably different among fishes which are generally low in carbohydrate and high in protein. Anthony et al. (2000) conducted an experiment to estimate energy density of 1151 fish from 39 species by proximate analysis of lipid, water, ash-free lean dry matter, and ash contents and evaluate factors contributing to variation in composition. It was found from this research that energy density values varied widely within and between species and lipid content was the primary determinant of energy density. Meanwhile, near-infrared spectra contain absorbance bands mainly due to three chemical bonds, i.e., C-H (lipids, hydrocarbons), O-H (water, alcohol) and N-H (protein). Other chemical bonds may also exhibit overtone bands in the NIR region, yet they are usually too weak to be considered for use in analysis of complex mixtures such as foods. The key wavelengths associated with lipid as C–H overtones and protein as N–H stretch second overtone in near-infrared region have been well demonstrated by a number of researchers (Workman and Weyer, 2012; Vo-Dinh, 2014). Since HSI technique has been successfully applied to predict protein and fat in fish, it is reasonable to presume that this technique could be also effective for determining food calorie counts.

Therefore, this study was carried out to develop NIR hyperspectral imaging technique as a rapid and accurate method for determining the gross energy density value of each salmon fillet. The successful outcome of this study could provide the food industry with a reliable non-destructive alternative method for food caloric density measurement. To the best of our knowledge, this is the first study in developing a rapid and non-destructive measuring technique for food calorie values for the food industry.

2. Materials and methods

2.1. Sample preparation

A total of 85 farm-raised Atlantic salmon (*Salmon salar*) fillets were purchased from Marine Harvest Ireland Company. Once harvested, fresh salmon were immediately beheaded, filleted and then transported to laboratories of Food Refrigeration and Computerized Food Technology (FRCFT), University College Dublin (UCD), Ireland. All the fillets were stored on ice with a big plastic barrier during transport and the temperature inside the storage area was maintained at −1 °C to make sure fillets were fresh and of superior quality. Each fillet was about 200 g in different sizes and no any two fillets were cut from one fish. The salmon fillets were subsampled into a cuboid shape with approximate sizes of 4.0 cm × 4.0 cm × 3.0 cm (length × width × thickness) to acquire a total of 151 subsamples, which were obtained from different locations of salmon fillets with the purpose of ensuring an appropriate span of energy density values.

2.2. Image acquisition

Hyperspectral images were acquired in the reflectance mode by employing a laboratory-based pushbroom hyperspectral imaging system (900–1700 nm). Details of the system can be found elsewhere (Xu et al., 2016). Each salmon sample was individually placed on the translation stage and then conveyed to the field of view of camera with a speed of 2.7 cm/s. A complete three-dimensional hyperspectral image also named 'hypercube' (x, y, λ) was subsequently created with two spatial dimensions (x and y) and one wavelength dimension (λ). Hyperspectral images were stored in raw format and then exported to Matlab 8.5 R2015a software (The Mathworks Inc., MA, USA) for subsequent processing. As HSI system collects the detector signal intensity, rather than actual reflectance spectra, the original images were corrected into the reflectance hyperspectral images using standard calibration procedure described by Kamruzzaman et al., (2015).

2.3. Measurement of caloric density

After image acquisition, salmon samples were weighed, and dried for 20 h in a ventilated oven at 105 °C to reach a constant weight. Dried matters were subsequently weighted and pelletized to a homogeneous mixture. About 1.0 g pellets were precisely weighed and ignited in a bomb calorimeter (Model 6400, Parr Instrument Co., Illinois, USA) to measure caloric content. Replicate analyses were always made and a third pellet was analyzed if the caloric density values of the first two pellets differed more than 5% of each other. Caloric values for all pellets were averaged to estimate gross energy value (kJ/100g wet mass) of the sample.

2.4. Spectral data extraction

2.4.1. Image segmentation

Image segmentation is always regarded as an essential and fundamental step to separate the salmon sample from the background, as subsequent extracted data are highly based on the precision of this process (Kamruzzaman et al., 2012). A threshold value was determined by subtracting a low-reflectance band from a high-reflectance band. After this step, a binary mask for