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Hyperspectral imaging of ribeye muscle on hanging beef carcasses for tenderness assessment

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ABSTRACT

A prototype hyperspectral image acquisition system (λ = 400–1000 nm) was developed to acquire images of exposed ribeye muscle on hanging beef carcasses in commercial beef packing or slaughter plants and to classify beef based on tenderness. Hyperspectral images (n = 338) of ribeye muscle on hanging beef carcasses of 2-day postmortem were acquired in two regional beef packing plants in the U.S. After image acquisition, a strip steak was cut from each carcass, vacuum packaged, aged for 14 days, cooked, and slice shear force values were collected as a measure of tenderness. Different hyperspectral image features namely descriptive statistical features, wavelet features, gray level co-occurrence matrix features, Gabor features, Laws' texture features, and local binary pattern features, were extracted after reducing the spectral dimension of the images using principal component analysis. The features extracted from the 2-day images were used to develop tenderness classification models for forecasting the 14-day beef tenderness. Evaluation metrics such as tender certification accuracy, overall accuracy, and a custom defined metric called accuracy index were used to compare the tenderness classification models. Based on a third-party true validation with 174 samples, the model developed with the gray level co-occurrence matrix features outperformed the other models and achieved a tenderness certification accuracy of 87.6%, overall accuracy of 59.2%, and an accuracy index of 62.9%. The prototype hyperspectral image acquisition system developed in this study shows promise in classifying beef based on tenderness.

1. Introduction

Beef tenderness is the second most important quality attribute of beef, preceded only by safety, based on consumers' demand (NCBA, 2007). Recent studies reported that consumers can discern differences in tenderness while eating cooked beef and they are willing to pay a premium of $1.14–$2.76 per pound for guaranteed tender beef (Gao and Schroeder, 2007; Loureiro and Umberger, 2004). The National Beef Assessment Plan III conducted by the National Cattlemen's Beef Association in 2007 concluded that certifying a beef product as tender has more value than producing a tender product (NCBA, 2007). Currently, no nondestructive technology is available for real-time beef tenderness assessment. Hence, development of such a technology is of prime importance to the beef industry to meet the ever increasing consumer demand for guaranteed tender beef.

Konda Naganathan et al. (2008a) used a spectrograph-based visible/near-infrared (VNIR) hyperspectral imaging (HSI) system (λ = 400–1000 nm) to predict tenderness of 14-day aged, cooked beef from hyperspectral images of fresh ribeye steaks acquired at 14-day postmortem. In another study, they used a spectrograph-based, near-infrared (NIR) HSI system (λ = 900–1700 nm) to predict tenderness of 14-day aged, cooked beef from hyperspectral images of fresh ribeye steaks acquired at 3-day postmortem (Konda Naganathan et al., 2008b). Both studies used gray-level textural co-occurrence matrix (GLCM) analysis to extract second-order statistical textural features from hyperspectral images of beef ribeye steaks. Canonical discriminant models were developed using the textural features to classify beef samples into three tenderness categories: tender, intermediate, and tough.

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With a leave-one-out cross-validation procedure, the VNIR HSI system classified beef samples ($n = 111$) into three tenderness categories with 96.4% accuracy, based on the current status of tenderness (14-day aged VNIR hyperspectral images predicted 14-day tenderness categories). All of the tough samples were correctly identified. The NIR HSI system classified beef samples ($n = 314$) into three tenderness categories with an overall accuracy of 77% in a tenderness forecasting scenario (3-day NIR hyperspectral image features were used to predict 14-day tenderness categories). When two tenderness categories (tender and tough by pooling the intermediate samples into tender category) were used, the accuracy of the NIR HSI system increased to 94.6%.

Both the HSI systems mentioned earlier were laboratory scale bench-top systems that required excision of a one-inch thick ribeye steak from each carcass for image acquisition and tenderness assessment. This process takes time and degrades the value of primal cuts. To resolve these shortcomings and assess tenderness at plant level, the HSI systems should acquire images of the ribeye muscle on hanging beef carcasses (Fig. 1) and assess tenderness on-line. In addition, robust hyperspectral image analysis algorithms are needed to improve the accuracy and repeatability of tenderness assessment. Only a few image features such as the gray level co-occurrence matrix, wavelet, and Gabor features, have been used for beef and pork tenderness evaluation (Konda Naganathan et al., 2008a,b; Jackman et al., 2009a, 2010; Barbin et al., 2013). Additional feature sets need to be evaluated for their ability to discriminate tenderness. The objectives of this study were to: (1) develop a prototype hyperspectral image acquisition system for acquiring hyperspectral images of the ribeye muscle on hanging beef carcasses in commercial beef packing plants, (2) implement and compare different textural features for their ability to forecast 14-day aged beef tenderness classes such as tender and tough, and (3) conduct a third-party true validation of the system for classifying beef carcasses based on their 14-day tenderness.

2. Materials and methods

2.1. Prototype hyperspectral image acquisition system

A prototype hyperspectral image acquisition system (Fig. 2) was developed for acquiring reflectance images of ribeye muscle (*longissimus thoracis et lumborum*) on hanging beef carcasses in beef packing plants. The system consisted of an adjustable-height mobile console (Fig. 2a), a camera module (Fig. 2b), and a computer (2.83 GHz Intel quad core processor and 8 GB of RAM).

2.1.1. Camera module

The camera module (Fig. 2b) included a line scan camera (Model: MV1-D1312-160-CL-12, Photonfocus, Lachen, Switzerland), a spectrograph (V10E, Specim Spectral Imaging Ltd., Oulu, Finland), a lens (XENOPLAN 1.4/17-0903, Schneider Optics, Kreuznach, Germany), and a mirror scanner assembly. The spectrograph provided a spectral sensitivity in the visible-near infrared region (VNIR) ranging from 400 to 1000 nm and had a spectral resolution of 2.8 nm. Also, the spectrograph had a 30 μm slit and a numeric aperture of F/2.4. The Photonfocus camera provided a resolution of 1312 × 1082 pixels with a 12- bit grayscale. The camera had a 2D CMOS image sensor array with a quantum efficiency of greater than 50%. The lens had a focal length of 17 mm and a maximum aperture of 1.4. The system scans a single-spatial line of a target object, and the spectrograph disperses light from each line element or pixel to a spectrum. Thus, each spectral image contained spatial pixels in one axis (1312 pixels) and spectral pixels in the other axis (1082 pixels). To obtain a three dimensional (3-D) hyperspectral data cube, a mirror scanner was used to scan the ribeye muscle area.

2.1.2. Mirror scanner assembly

The mirror scanner assembly (Fig. 2b) was a part of the camera module and included a mirror, a white-painted dome, and locating plates. The mirror was positioned at a 45° angle, so that the

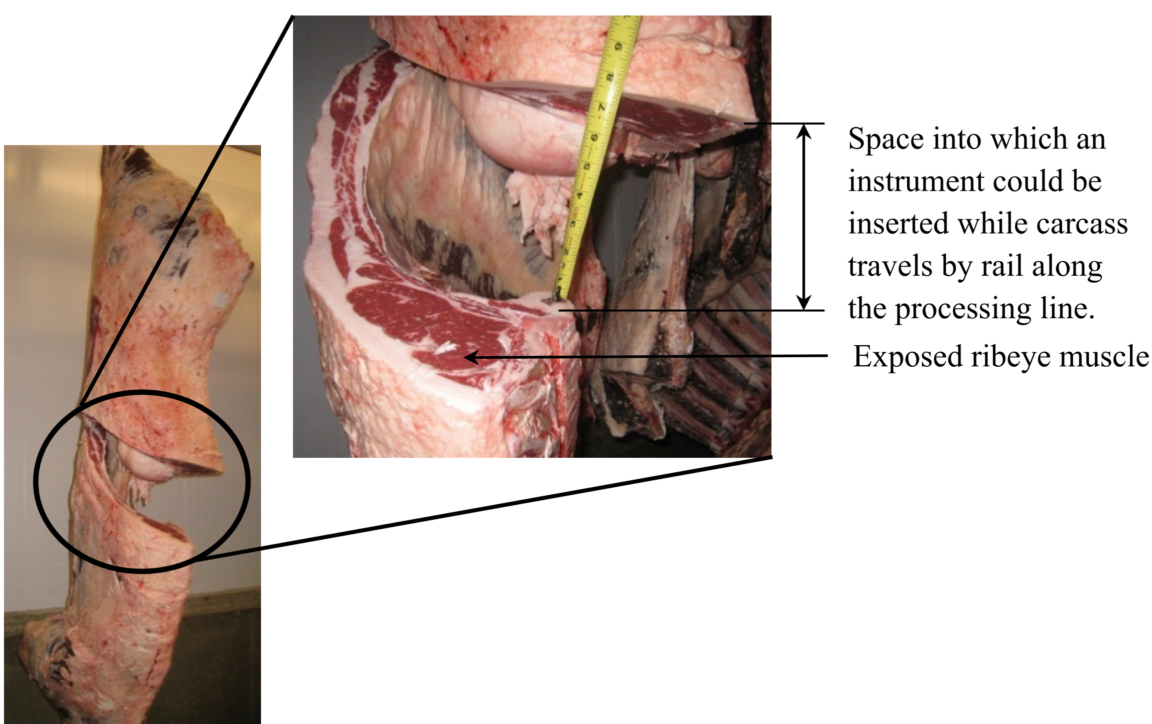

Fig. 1. A hanging beef carcass showing the exposed ribeye muscle between the 12th and 13th rib and available vertical space between the forequarter and hindquarter for placing an instrument to acquire an image of the ribeye muscle.