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Development of a multichannel hyperspectral imaging probe for property and quality assessment of horticultural products

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ABSTRACT

This paper reports on the development and calibration of a new multipurpose, multichannel hyperspectral imaging probe for property and quality assessment of horticultural and food products. The new multichannel probe consists of a 910 μm diameter fiber as a point light source and 30 light receiving fibers of three sizes (i.e., 50 μm, 105 μm and 200 μm) arranged in a symmetrical pattern, for simultaneous acquisition of 30 spatially-resolved reflectance spectra of horticultural and food samples with either flat or curved surface over the spectral region of 550–1650 nm. Three types of calibration for the multichannel probe were carried out, i.e., linearity calibrations for each fiber of the hyperspectral imaging system to ensure consistent linear responses of individual fibers, spectral response calibrations of individual fibers for each fiber size group and between the three groups of different size fibers, and optical property calibrations using four reference liquid samples. The calibration results showed that all 30 fibers had high linearity with exposure time with the coefficient of determination being greater than 0.990 for wavelengths greater than 700 nm; however, linear responses, as measured by the slope and intercept, for the individual fibers differed greatly and also varied with wavelength. After the calibrations, the probe was able to measure the scattering coefficient of the reference liquid samples with the relative errors between 3%–21%, whereas higher measurement errors were obtained for the absorption coefficient due to low absolute absorption values for the samples. Furthermore, the probe was demonstrated for measuring the absorption and scattering coefficients of tomato fruit at four maturity stages for the wavelengths of 550–1350 nm.

1. Introduction

Visible and near-infrared (Vis/NIR) spectroscopy has been one of the most successful techniques for nondestructive measurement of chemical constituents and quality attributes of horticultural and food products (Kumar et al., 2015; Lammertyn et al., 1998; Nicolai et al., 2007). The technique is based on measuring the remission of light from the sample in the form of reflectance, interactance, or transmittance. Since the measured light is related to the composition and structure of the sample and is also wavelength dependent, Vis/NIR spectral measurement can thus offer quantitative information about the properties and quality of food products. The Vis/NIR light is normally referred to the electromagnetic region of 400–2500 nm, although the actual spectral region covered by individual Vis/NIR spectroscopic instruments may vary, depending on type of detector used. For instance, CCD-based Vis/NIR spectroscopic instruments typically cover the wavelengths of 400–1000 nm, whereas InGaAs-based spectroscopic instruments have a typical spectrum of 900–1700 nm. It is well known that light in the spectral region of 700–1300 nm has good penetration in food and biological tissues, and its penetration capability decreases dramatically beyond 1300 nm due to strong absorption of water in biological materials. Consequently, most Vis/NIR spectroscopic measurements for food evaluation are carried out in reflectance mode, while transmittance and interactance measurements, where the measured light has gone longer pathlengths, are usually confined to the wavelengths of 400–1000 nm.

As light enters a turbid medium, it simultaneously undergoes the processes of absorption due to chemical constituents and multiple scattering due to the presence of scattering particles as well as variations in the refractive index from one component to another. Light attenuation in turbid biological materials is mainly determined by the absorption coefficient and reduced scattering coefficient (Lu, 2016; Michels et al., 2008). Light scattering is related to the structural or physical characteristics of the material, whereas absorption is primarily

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dependent on the chemical constituents (Cen et al., 2012; Qin and Lu, 2008). Thus, measurement of the absorption and scattering properties could provide more detailed information on the chemical properties and structural characteristics of food products. However, conventional Vis/NIR technique only measures an aggregate amount of light acquired from a specific area (or point) of the sample without providing spatially resolved information. The technique is thus unable to directly measure the absorption and scattering properties of horticultural and food products. Moreover, conventional Vis/NIR technique may not adequately assess horticultural and food samples whose properties vary spatially or with depth, because it lacks the capability of providing spatially-resolved measurements.

Over the past two decades, considerable research in the biomedical field has been directed towards the development of techniques for measuring optical absorption and scattering properties of biological tissues. Among the developed techniques are spatially-resolved, spatial frequency, time-resolved and frequency domain, which are based on the diffusion approximation theory. These techniques have been used in biomedical research for noninvasive diagnosis and monitoring of abnormal tissues within the human's heterogeneous body (Nichols et al., 2012; Zhou et al., 2015a; Zonios et al., 2010). While suitable for assessing homogeneous tissues at greater depth or multi-layered tissues, time-resolved and frequency domain techniques are sophisticated and expensive in instrumentation, and time consuming in measurement. Hence, their application to horticultural and food products has so far been limited. Spatially-resolved spectroscopy (SRS), on the other hand, measures reflectance at different distances from the point light source of constant intensity, from which the absorption and scattering properties are estimated using an inverse algorithm for the diffusion approximation model (Cen et al., 2016). It should be mentioned that the term 'reflectance' is used throughout this paper in order to keep it consistent with the prevailing use of the term for spatially resolved technique, although the term 'interactance' or 'semi-transmittance' is also commonly used when the light is measured from locations separated from the incident point in many reported Vis/NIR studies. Spatially-resolved spectra contain the information about the samples at different depths due to different source-detector distances, as the transport path of photons generally forms a "banana-shape" in biological tissues (Ohnishi et al., 2003). Hence they are suitable for assessing the condition and properties of tissues at different depths. The technique has been used for noninvasive diagnosis of tumors in humans (Rosenbaum et al., 2016; Tuchin and Tuchin, 2007). Compared to the time-resolved and frequency domain techniques, SRS is less complicated in instrumentation and relatively easy to use, and generally covers a broader spectral region. It has thus received much attention by researchers in food and agriculture in recent years (Hu et al., 2015).

Currently there are two main measurement configurations for SRS, i.e., fiber probe-based and spectral imaging-based. Fiber probe-based SRS uses a point light source of constant intensity and single or multiple detection fibers arranged at different distances from the light source. A single fiber detection configuration has the flexibility of changing the measured position or source-detector distance by moving the optical fiber relative to the light source. Xia et al. (2008a, 2008b) used this configuration to acquire spatially-resolved diffuse reflectance data for beef muscles over the spectral range of 600–950 nm, from which the reduced scattering coefficient and absorption coefficient were obtained for predicting the tenderness of beef muscles. Kemsley et al. (2008) reported a preliminary study for an optical system, in which the illumination fiber was fixed, while the detecting fiber coupled with a lens rotated around a cylindrical phantom to acquire angularly optical signals. The authors showed that it was possible to reconstruct a 2-D sensitivity image for a cylindrical potato sample, which could then be used for detecting internal defect. However, the moving of the detecting fiber for measuring food samples at different positions can introduce errors in measurement because the surface of the food samples may not be smooth or flat. Moreover, the sequential data acquisition method is time consuming, and the properties of the sample could change during the measurement. Besides, the fluctuation of light source output during long measurement time can also result in errors for optical property measurements. The fiber-array probe has thus been considered as a preferred configuration to overcome some of the shortcomings of repositioning the fiber during measurement. With this configuration, multiple detection fibers are arranged at different distances from the light illumination fiber and coupled to a multiplexer to sequentially obtain reflectance signals from the different detection fibers by a single spectrometer. A fiber-array configuration with the light source and detection fibers arranged in a line, was used to estimate the optical properties of turbid media at 633 nm (Zhou et al., 2015b). While it eliminates the need of repositioning the fiber, the fiber-array configuration with a multiplexer also needs sequential scanning of multiple fibers. To overcome this problem, researchers (Do Trong et al., 2014a, 2014b; Herremans et al., 2013) developed a fiber-array probe configuration by arranging five detection fibers and an illumination fiber on the round, flat probe with fixed distances of 0.3–1.2 mm; the other end of the detection fibers is linked to an imaging spectrograph coupled to a CCD camera covering the wavelength range of 500–1000 nm. This fiber-array probe allows simultaneous measurement of spectral signals at different source-detector distances. However, since all fibers are fixed to the inflexible probe, the configuration is not suitable for horticultural and food samples of curved surface or irregular shape. Moreover, with so few detection fibers (5) and such a short distance span (up to 1.2 mm), it would be difficult to measure the optical properties of horticultural and food products at greater depths.

A hyperspectral imaging-based spatially-resolved spectroscopic technique has been developed for measuring the optical properties of horticultural and food products (Cen and Lu, 2010; Cen et al., 2012, 2013; Lu et al., 2010; Qin and Lu, 2008). It employs a line scanning hyperspectral imaging system to acquire spatially-resolved reflectance over the spectral range of 400–1000 nm for a distance range of up to 15 mm from the point light source. The technique has advantages of being noncontact, fast and higher in spatial resolution for measuring the optical properties. It has been used to quantify the scattering and absorption properties of food products including fruits and vegetables as well as for assessing quality attributes such as firmness and soluble solids content. The technique is suitable for food samples of flat surface or samples with relatively large sizes. When the surface of the sample is curved, errors in signal acquisition due to the surface curvature can be introduced. Hence corrections to the measured spatially-resolved reflectance spectra would be needed to ensure accurate estimation of optical properties. However, such corrections are often complicated and may not achieve desired results. Furthermore, the wavelength range covered by the hyperspectral imaging system for optical property measurement is limited to the Vis/NIR region of 400–1000 nm. Extension to longer wavelengths of the NIR region is desirable in order to obtain more useful information about horticultural and food samples.

Many intact horticultural products, such as fruits and vegetables, are of irregular shape or curved surface, and their composition and structural properties vary spatially and with depth. While SRS technique has advantages of measuring the optical absorption and scattering properties, the existing single-fiber and fiber-array probe configurations are only suitable for horticultural and food samples with flat surface. Moreover, due to the limitations in instrumentation, the fiber-array probe configuration only allows a few optic fibers (e.g., up to five) and a short detection distance, which are suboptimal for optical property measurements that requires covering a greater range of distances. While the hyperspectral imaging-based SRS technique is advantageous, compared to the fiber-array configuration, it has a narrower spectral region (400–1000 nm) and also lacks the flexibility of measuring samples of irregular or curved shape.

This research was therefore aimed at developing a new multipurpose optical detection probe, using a multichannel hyperspectral imaging system, for simultaneous, fast acquisition of spatially-resolved