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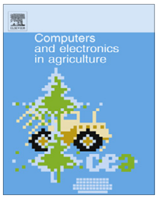

Original papers

# Influence of surface curvature on light-based nondestructive measurement of stone fruit

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A B S T R A C T

The propagation of photons in stone fruit tissue was simulated with the Monte Carlo (MC) method. A model of concentric-spherical-layered tissues was built for intact stone fruit. Peaches were used as typical representatives of stone fruit. Diffuse reflectance and inspection efficiency were calculated using the concentric-spherical-layered model. The simulation results were compared with those expected from the classic infinitely-wide planar layered model. Surface curvature increases the diffuse reflectance but decreases the inspection efficiency, especially for the case of short source-detector distance. For small size fruit items, errors in the planar layered tissues model would be increased due to their greater surface curvature. This paper suggests a need to take into account the influence of surface curvature to retrieve the optical absorption and reduced scattering coefficients from Vis-NIR spectroscopy data for fruit. And the experimental arrangements such as the source-detector distance and the integration time for the spectrometer require adjustment accordingly.

## 1. Introduction

Visible-near infrared (Vis-NIR) spectroscopy measurements have been utilized for fruit quality inspection for many years (Nicolaï et al., 2007). The fruit is irradiated with Vis-NIR radiation, and the reflected or transmitted radiation is measured. The radiation interacts with fruit tissue through both absorption and scattering. While absorption in the Vis-NIR range is related to some important chemical quality attributes such as the total sugar content, scattering is related to the microstructure of the fruit (Oey et al., 2007). With the optical properties retrieved from the Vis-NIR spectroscopy measurements, the quality and internal structure of fruit can be deduced by inverse methods such as linear regression techniques and nonlinear regression techniques (Nicolaï et al., 2007). Unfortunately, the light-based techniques of fruit quality inspection are still not well developed, and their accuracy and robustness is often limited. So there is a growing demand for accurate and fast models to quantitatively understand light transport process and features in fruits.

Fruits are a kind of highly scattering turbid media. Although the radiation transport equation (RTE) is the basis of the general solution of light transport in turbid media (Ishimaru, 1978; Schweiger et al., 1995), its application in complex geometrics is hindered by difficulties in obtaining the analytical solution to RTE. Monte Carlo (MC) simulation methods solve the RTE numerically and have successfully tested the validity of analytical algorithms obtained from the RTE (Wang and Jacques, 1992). MC based methods have been widely utilized to ray-trace individual photons in biological medium such as fruits, vegetables, and human tissues (Fraser et al., 2003; Okada et al., 1997; Tsai et al., 2001; Wang and Liang, 1999; Wilson and Adam, 1983). Several studies (Baranyai and Zude, 2009; Fraser et al., 2003; Qin and Lu, 2009) have used MC simulation to investigate light propagation in fruit tissues. However, these simulations consider the fruit to be either an infinitely-wide planar layered turbid media (Baranyai and Zude, 2009; Qin and Lu, 2009), or a homogeneous sphere of tissue (Fraser et al., 2003). Actually, fruits are neither infinitely-wide nor homogeneous. Take stone fruit (or drupe) for example, it is an indehiscent fruit in which an outer fleshy part surrounds a shell of hardened endocarp with a seed inside. The geometries and optical properties of different structures of stone fruit would inevitably affect the light transport features.

In this paper, peaches were used as typical representatives of stone fruit. We developed a MC model of concentric-spherical-layered tissues and compared the simulation results with those obtained by the planar layered tissues model. The influence of surface curvature on light-based nondestructive inspection of stone

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fruit was assessed. The analysis would result in a better insight into the interaction of light radiation with the fruit tissue, and help the development of optical techniques for fruit quality inspection.

## 2. Materials and methods

### 2.1. Simulation models for stone fruit

MC modeling of light transport in multi-layered tissues (MCML) coded in standard C has been developed and brought to public domain by Wang and Jacques (1992). It has been widely used for various studies. MCML simulation for light transport in stone fruit is illustrated in Fig. 1(a). The skin, flesh and core are considered to be infinitely-wide planar layered tissues. Each layer is assumed to be homogeneous, and is described by the following parameters: the thickness $d$, the refractive index $n$, the absorption coefficient $\mu_a$, the scattering coefficient $\mu_s$, and the anisotropy factor $g$. The escape of photons at the upper surface is recorded as diffuse reflectance $R_d$. This model has been adopted by several researchers though sometimes the skin layer or the core layer is neglected (Fraser et al., 2003; Qin and Lu, 2009).

Considering the actual geometries of stone fruit, a model illustrated in Fig. 1(b) is established. The fruit is considered to be a concentric-spherical-layered turbid medium consisting of three layers (skin–flesh–core layers). Each layer is assumed to be homogeneous, and is described by the thickness $d$ (or the outside radius $r_0$ and the inside radius $r_1$), the refractive index $n$, the absorption coefficient $\mu_a$, the scattering coefficient $\mu_s$, and the anisotropy factor $g$. The escape of photons at the surface is recorded as diffuse reflectance $R_d$. MCML code is modified in this study.

### 2.2. Monte Carlo simulation

MC simulation tracks millions of photons of the incident light beam inside the fruit tissue. The reader interested in a more detailed description of MC for light propagation in biological medium is referred to Wilson and Adam (1983), and in MCML code, to Wang and Jacques (1992). A brief outline of how the MC is performed is presented as follows:

To improve computation efficiency, the MC simulation propagates many photons as a packet simultaneously rather than individual photons, which will terminate at the first absorption event. Each photon packet is assigned a weight representing the amount of light available for absorption or scattering. When a photon packet is launched, it is injected orthogonally into the tissue, i.e. directed toward the center of the sphere in the concentric model, with an initial weight $w_0 = 1$. The specular reflectance $R_{sp}$ from the surface is calculated using Fresnel equations (Born and Wolf, 1999), and the remaining photon packet with weight $w = 1 - R_{sp}$ is transmitted into the fruit tissue. The step size between successive photon-tissue interactions is calculated based on a random sampling of the probability distribution for the photon's free path:

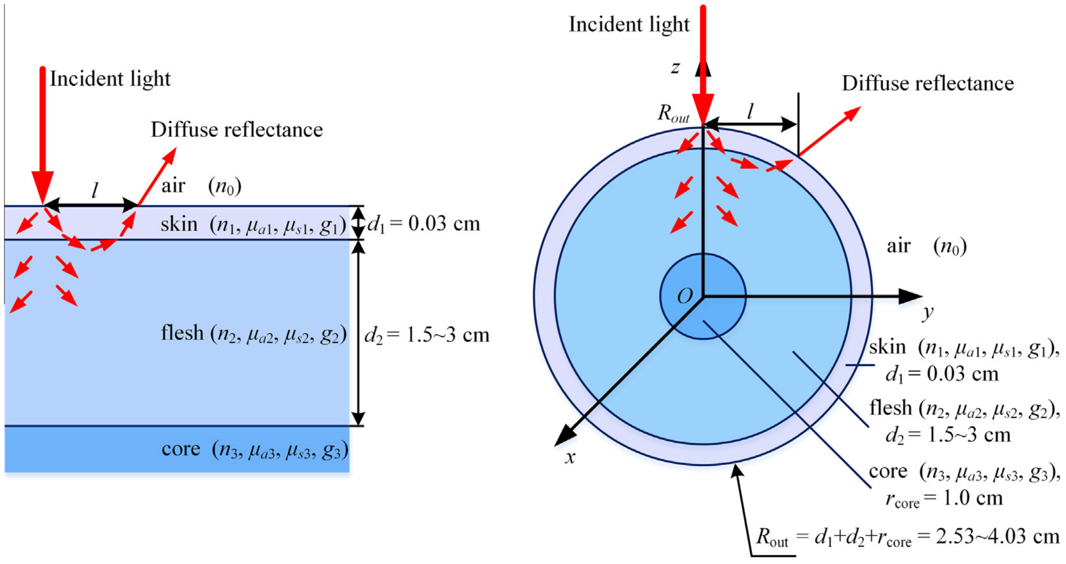
$$s = \frac{-\ln(\xi)}{\mu_a + \mu_s} \tag{1}$$

where $\xi$ is a random number uniformly distributed over the interval (0,1). At each interaction site, the weight of the photon packet is decreased by Eq. (2) due to absorption.

$$\Delta w = w\frac{\mu_a}{\mu_a + \mu_s} \tag{2}$$

The photon packet with the new weight will scatter and change propagation direction. The scattering angle $\theta$ is determined by the Henyey–Greenstein phase function (Henyey and Greenstein, 1941). Then, a new step size is calculated, and the photon packet moves this new step.

During a step, the photon packet may hit the boundary or the interface (including the air–skin, skin–flesh, and flesh–core interfaces). If this is the case, the proportion of internal reflection $R(\alpha_i)$ is defined by Snell's refraction law and Fresnel's equations (Born and Wolf, 1999). Whether the photon packet is transmitted or internally reflected is determined statistically by generating a random number $\xi$, and comparing $\xi$ with $R(\alpha_i)$. If the photon packet transmits into the ambient medium or into the core layer, its



(a) (b)

**Fig. 1.** Two types of models for stone fruit. (a) The model of infinitely-wide planar layered tissues (MCML). The skin, flesh and core are considered to be infinitely-wide planar layered tissues. Photons that exit the surface are accumulated as the diffuse reflectance. The probe is placed on the surface of the fruit with the source-detector distance $l$ away from the incident point. (b) The model of concentric-spherical-layered tissues. The skin, flesh and core are considered to be concentric-spherical layered tissues. The probe is placed on the surface of the fruit. The source-detector distance $l$ is defined as the horizontal distance for better comparison with the planar model.