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Light transmission analysis of laser scattering imaging and Monte Carlo simulation in apple issue

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Abstract. The light transmission characteristics in apple tissue were studied by using laser scattering imaging and Monte Carlo (MC) simulation methods. The optical parameters of apple tissue were analyzed by laser scattering visual inspection system, and the scattering coefficient and absorption coefficient were obtained by least-square fitting method. MC method was used to simulate the light transmission of intact apple tissue. The results of MC simulation and laser scattering imaging experiments showed that the maximum error of diffuse reflectance at different locations did not exceed 3%. The internal quality of fruit is closely related to the absorption coefficient and scattering coefficient of light. The studying of the apple issue light transmission characteristics and MC simulation can help design the more effective and non-destructive detection system for fruit internal quality.

1. Introduction

Due to the differences in the internal composition and external characteristics of the fruit, the absorption and scattering properties show different when a beam of light with a certain wavelength illuminates the fruit surface. Based on the optical properties, the quality information of the fruit can be obtained by measuring the absorption coefficient and scattering coefficient. The non-destructive testing of fruit quality using the issue optical properties has become an important development direction for fruit quality testing.

The optical detection technologies for fruit quality inspection mainly include near-infrared spectroscopy [1], multi-spectral [2] and hyperspectral imaging methods [3]. These detection methods have high precision, but they need long detection time and high cost, which limits the application in the fruit detection field. Laser scattering machine vision detection system based on suitable wavelength laser has the characteristics of low cost, high speed and flexibility, and has great potential and feasibility in the field of fruit detection. Tu et al. [4] used laser light scattering technology to classify the ripening period of tomato. Cho et al. [5] used the technique to predict the apple's SSC and hardness. Some commercially available laser scattering instruments have also been used for the classification and grading of fruits.

To develop the technique of laser fruit internal quality detection, we firstly need to study the light transmission characteristics of fruit tissue, and establish a relationship model between the light characteristics and the internal quality of the fruit. The optical properties of the fruit tissue are mainly described by absorption coefficient, scattering coefficient and refractive index, etc. The interaction between fruit and light is a complex phenomenon. It is still a great challenge to improve the accuracy and robustness of detection by extracting useful optical information from fruit tissue.

The Monte Carlo (MC) method, based on the random number statistics, is an effective tool for simulating light transmission in tissues [6]. It provides a flexible and rigorous solution for solving the problem of light transmission in turbid media. The researches of light propagation based on MC simulation method has been studied in fruit tissues [7] as well as in human tissue [8].

In this paper, the absorption coefficient and scattering coefficient were measured by laser scattering visual inspection system. MC simulation method was used to simulate the light transmission law of intact apple tissue. The consistency of MC simulation results and experimental results was compared. The study of optical transmission characteristics helps to design a more effective non-destructive inspection system for internal quality of fruits.

2. Materials and methods

2.1. Apple

Fifty Red Fuji apples were used in this study. The materials were required to be similar in maturity, color and intrinsic quality, and were not bruised mechanically. These apples were washed with water first and then dried with a dry cloth. They were stored at a room temperature of 25 ℃ during the experiment period.

2.2. Diffuse reflection approximation theory

The light transmission in apple tissue is determined by the optical properties of the tissue. Parameters that describe the tissue optical properties mainly include the absorption coefficients μ_a and the scattering coefficients μ_s. The optical properties not only relate to the wavelength of the selected laser, but also relate to the sample parameters such as sugar content, hardness and moisture.

The light transmission theory in fruit tissues has analytical theory and radiation transmission theory [9]. The derivation of analytical theory is very complex, which limits its range of application. Radiation transmission theory directly deals with the transmission energy in randomly scattered tissues. The research process is relatively intuitive and widely used.

The detection system uses a monochromatic laser to continuously illuminate the surface of the apple. The light distribution in the tissue is a steady state independent of time. Under the diffusion approximation theory, the radiative transfer equation can be simplified to obtain the diffusion approximation equation to solve diffuse reflectance [10]. Starting from the conservation of the number of particles, the solution to the diffusion approximation equation under the epitaxial boundary conditions is:

$$R(\rho) = \frac{1}{4\pi}[z_0(\mu_{eff} + \frac{1}{r_1})\frac{\exp(-\mu_{eff} r_1)}{r_1^2} + (z_0 + 2z_b)(\mu_{eff} + \frac{1}{r_2})\frac{\exp(-\mu_{eff} r_2)}{r_2^2}] \quad (1)$$

Where, $z_0 = \frac{1}{\mu_s + \mu_a}$, $\mu_{eff} = [3\mu_a(\mu_a + \mu_s)]^{1/2}$, $z_b = 2\frac{1+\mu_{eff}}{1-\mu_{eff}}D$, $D = \frac{1}{3(\mu_a + \mu_b)}$, $r_1^2 = z_0^2 + \rho^2$, $r_2^2 = (z_0 + 2z_b)^2 + \rho^2$, μ_{eff} is the effective attenuation coefficient, ρ is the vertical distance from the diffuse light spot to the light incident point on the tissue surface, z_0 is the mean free path of the photon transmission, and z_b is the average free path of the photon transmission outside the media surface.

It has been proved by experiments that the error of the result calculated by Eq.(1) is relatively small. In this paper, we choose Eq.(1) to invert and obtain the parameters μ_a and μ_s of the medium.

Using the laser diffuse reflectance system and regression analysis method, the optical parameters of the apples was fitted, which are $\mu_a = 0.65cm^{-1}$ and $\mu_s = 0.86cm^{-1}$.

2.3. Monte Carlo simulation

The MC method has become one of the most commonly used methods for simulating photon transport within biological tissues. It uses the computer to track the scattering, absorption and transmission of each incident photon on the premise of assuming the parameters of the optical properties of the biological tissue. A large number of photons are counted and averaged, and finally the distribution of the light inside the tissue and the surface is given [11]. Wang et al. [12] developed an MC program that simulates the steady state optical forward propagation law in multi-layer structures. This program is widely used.

A beam of infinitely fine collimated light is incident on the tissue surface. The initial weight of the incident photon is 1.The photons will be reflected on the tissue surface, and the specular reflectance is:

$$R_{sp} = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \quad (2)$$

The weight of the photons is reduced to M=1-Rsp, n_1 is the air refractive index, and n_2 is the refractive index of the fruit tissue. The step length of the photon packet motion depends on the cumulative probability distribution of the mean free path. The photon packet is randomly distributed at each scattering point, so the motion step size of photon packet is:

$$s = -\frac{\ln \xi}{\mu_a + \mu_s} \quad (3)$$

Where ξ is a uniformly distributed random number in the range [0,1]. When photons enter the fruit tissue, they are absorbed and scattered by the fruit tissue in each step movement.

The absorption will cause the attenuation of photon weight factor, and attenuated weight becomes

$$w_{n+1} = w_n \left(1 - \frac{\mu_s}{\mu_a + \mu_s}\right) \quad (4)$$

When photons are transmitted in the tissue, the propagation direction will be changed by the scattering of the tissues. The position of the next scattering point is calculated according to the scattering step s. The probability distribution of the scatter angle cosine is given by the Henyey-Greenstein phase function [13]:

$$p(\cos\theta) = (1 - g^2) / [2(1 - 2g\cos\theta + g^2)^{\frac{3}{2}}] \quad (5)$$

Where, the factor g is the average scattering cosine. When $g = 1$, it means complete forward scattering; when $g = -1$, it means complete backscatter.

A photon transmitted in an organization can escape from the tissue by the reflection or transmission of the boundary, and it is considered that the photon naturally terminates. For a photon still traveling in the organization, if its weight is less than the pre-set threshold weight w_{th} (in this article $w_{th} = 0.0001$), the "roulette" method is applied for the processing [14]. This method makes the photon termination closer to the natural termination, and the simulation result has higher accuracy.

3. Results and discussion

3.1. Experimental verification of the MC simulation

A visual inspection system using laser scattering images was used to verify the MC simulation. The system consists of a laser, a convex lens, a loading platform, an image acquisition card, and a computer. The laser image visual inspection device schematic is shown in Figure 1. In the MC simulation, the incident beam geometry is usually reduced to infinity. In order to increase the imaging resolution and obtain more information about the quality of fruit inside, the laser beam is focused by the objective lens to generate a photon beam with a radius of 0.5 mm, and incident light illuminates the surface of the sample with a small incident angle($5^{\circ}C \sim 10^{\circ}C$).

The intensity distribution of the light beam focused by the objective lens on any section is generally a Gaussian function. With the incident point of the laser as the center, the brightness of diffuse reflection light distribution gradually attenuates, and the diffuse reflection light distribution pattern of the sample surface is collected by adjusting the focal length of the CCD and the amount of light passing. The image acquired by the CCD was sent to a computer for image analysis and processing. To reduce noise, the experiment was conducted in a dark room. Inexpensive semiconductor lasers was used for lasers. This project selected the semiconductor laser LSR635NL-50 of Ningbo Yuanming Laser Technology Co., Ltd., with the wavelength 635 nm and the power 30 mW.

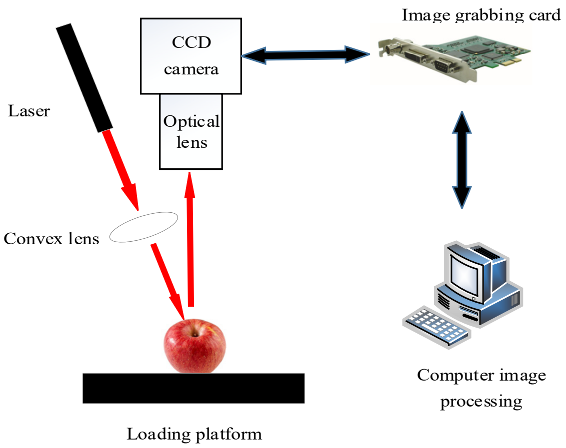

Figure 1. Schematic of the setup for laser image visual inspection

The light diffuse reflection and internal photon absorption in fruit tissue are simulated by MC, which is shown in Figure 2 [7]. Photons are incident on the surface of the fruit. Some of them are specularly reflected, and the rest of the photons are transmitted to the fruit tissue. The diffuse reflection array R(r) represents the photons exiting the tissue surface, and the absorption array A(r,z) represents photons absorbed within the fruit tissue. The simulation results obtained by the above method are based on the assumption that the light source is an infinitely narrow photon beam. In order to increase the simulation accuracy, the light source profile of the imaging system is convolved with the original simulation result to produce a photon beam with a radius of 0.5 mm, which is the same size as the beam used in the laser imaging system.

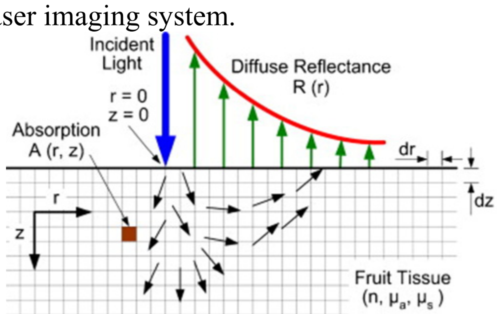

Figure 2. MC simulation for diffuse reflectance and absorption in apple tissue

The gray value of the image is obtained by CCD in the imaging system represents the scattering intensity. The gray image analysis was performed by the least squares method. $R(\rho)$ is calculated according to the Eq. (1). The absorption coefficient and scattering coefficient of the complete apple were obtained by fitting, which are $\mu_a = 0.65 \ cm^{-1}$ and $\mu_s = 0.86 \ cm^{-1}$.

3.2. MC parameter selection

The simulation parameters of the selected MC model were shown in Table 1. The fitted optical property parameters of the experimental system were used as the initial values of the simulation.

The absorption and scattering coefficients were 0.64 cm^{-1} and 0.86 cm^{-1} respectively. In order to obtain relatively high accuracy, the number of simulated photons is 100000. The refractive indices of air and apple tissues are 1.00 and 1.34, respectively. The radial distance (r) is 2 cm and the thickness (z) is 2.4 cm, respectively. The spatial resolution is 0.1 mm.

Table 1. Input parameters for MC simulation of light transport in apple tissue.

Parameter	**Value**
Number of photons	100000
Radius of the light beam	0.5 mm
Air refractive index n0	1.00
Apple refractive index n1	1.34
Absorption coefficient μ_a	0.64 cm^{-1}
Scattering coefficient μ_s	0.86 cm^{-1}
Spatial resolution of radial distance (dr)	0.1 mm
Spatial resolution of tissue depth (dz)	0.1 mm
radial distance r	2 cm
Thickness z	2.4 cm

3.3. Comparison of experiment and MC simulation results

The calculation of the photon transmission inside the fruit tissue was simulated by using the C language program. Focusing on the incident light spot, the diffuse reflectance at different radial positions is calculated.

The gray value of the image obtained by CCD was normalized as the experimental diffuse reflectance. The diffuse reflectance data of the MC simulation and the experiment is plotted in Figure 3. Within a radius of 2 cm, the maximum error between MC simulation results and measurement results is 3%, which showed the MC simulation results have sufficient accuracy. Therefore, it is feasible to use the method to obtain the optical properties of apples.

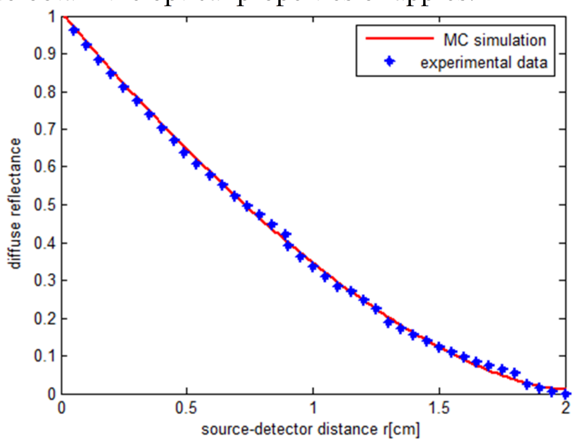

Figure 3. The result of experiment and MC simulation of apple issue

4. Conclusions

The optical parameters of apple tissue were analyzed by laser scattering visual inspection system, and the scattering coefficient and absorption coefficient were obtained by least-square fitting method. MC method was used to simulate the light transmission of intact apple tissue. The gray value of the CCD image of the experimental system is used to represent the diffuse reflectance of the fruit tissue. The results of MC simulation and laser scattering imaging experiments show that the maximum error of diffuse reflectance at different locations does not exceed 3%. The internal quality of apples is closely related to the absorption or scattering coefficient of light. By studying the light transmission characteristics of fruit, it can help to establish a relationship model between the light characteristic parameters and the internal quality. MC simulation can calculate the optimal configuration without the large number of experimental measurements, and it can help to design the more effective fruit quality inspection system.

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