Application of time-of-flight near infrared spectroscopy to apples

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Introduction

Consumers' demands, with respect to agricultural products, are becoming increasingly diverse. The producer must not only supply them safely while maintaining freshness, but also assure the taste and nutritional values. Therefore, it is desirable for the horticultural industry to evaluate these indices correctly without waste of time and energy. For example, the nondestructive detection of water core and sugar content in apples would be of considerable value to the fresh-apple industry.

A number of techniques and devices for either the transmittance or reflectance method, which could detect inner information of apples (for example, sugar content or water core), were proposed previously.[1–4] However, the behaviour of transmitted light from an agricultural product is directly affected by the physical and chemical properties of tissues, so that it is very important to examine the optical characteristics of the tissue and its origin in detail from a new viewpoint. In this study, an optical measurement system, which was mainly composed of a parametric tunable laser and a near infrared (NIR) photoelectric multiplier, was introduced to achieve this purpose by using time-of-flight near infrared spectrometer (ToF-NIR).[5,6] This system combines the best features of the spectrophotometer and the laser beam and, more advantageously, that the time-resolved profile of transmitted output power can be measured sensitively in nanoseconds. The combined effects of the condition of water core, sugar content and sample diameter on the time-resolved profiles were investigated in detail.

Material and methods

The samples used were "Fuji" apple (*Malus domestica* Borkh.cv.Fuji) (location:Aomori, Japan) which were between 80–90 mm in diameter. The condition of water core was defined by visual evaluation. The sugar content, measured by a refractometer, varied from 11.6 to 14.8 °Brix. The Q-switched Nd:YAG laser was employed as the exciter laser. The wavelength of the pulsed laser could be turned from 500 to 1100 nm by an optical parametric oscillation of a BBO crystal.[7,8]

The transmitted output power from the sample was measured by an NIR photoelectric multiplier, having a spectral response ranging from 300 nm to 1700 nm, which was cooled to –80°, through an fibre-opic cable, having a diameter of 7 mm. A Si pin-type photodiode was placed near the optical parametric oscillator to generate a trigger signal. The fibre-opic cable was directly in contact with the apple, which was enclosed in aluminum foil to keep out stray light. Furthermore, the sample, the cooling box containing the NIR photoelectric multiplier and the fibre-opic cable were also covered with black cloth. The sampling time and the average number of the transmitted output power were 100 ns and 100 times, respectively. The equator of the apple was irradiated vertically with the pulsed laser and

Near Infrared Spectroscopy: Proceedings of the 10th International Conference

the transmitted output power was measured on the restricted position of the equator using the fibre-opic cable.

Outline of time-resolved profile

The time-resolved profile refers to the variation of the intensity of the detected light beam with time. We focused on some typical parameters representing the variation of the time-resolved profile. The normalised time-resolved profiles of a sound apple (89 mm in diameter) and its cuticle (thickness = 1.0 mm) are shown in Figure 1. In this study, the time-resolved profile of the cuticle was employed as the reference.

The variations of the peak maxima A_t, the time delay of peak maxima Δt and the variation of the full width at half maximum of the profile Δw were examined under the experimental measuring conditions, respectively.

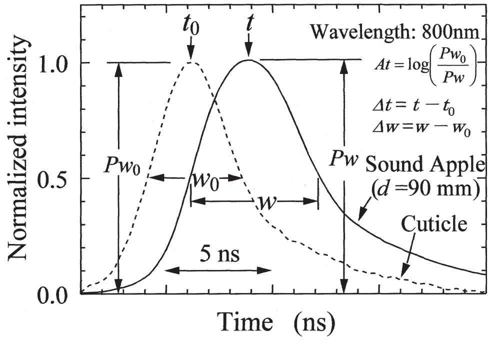

Figure 1. Normalised time-resolved profiles.

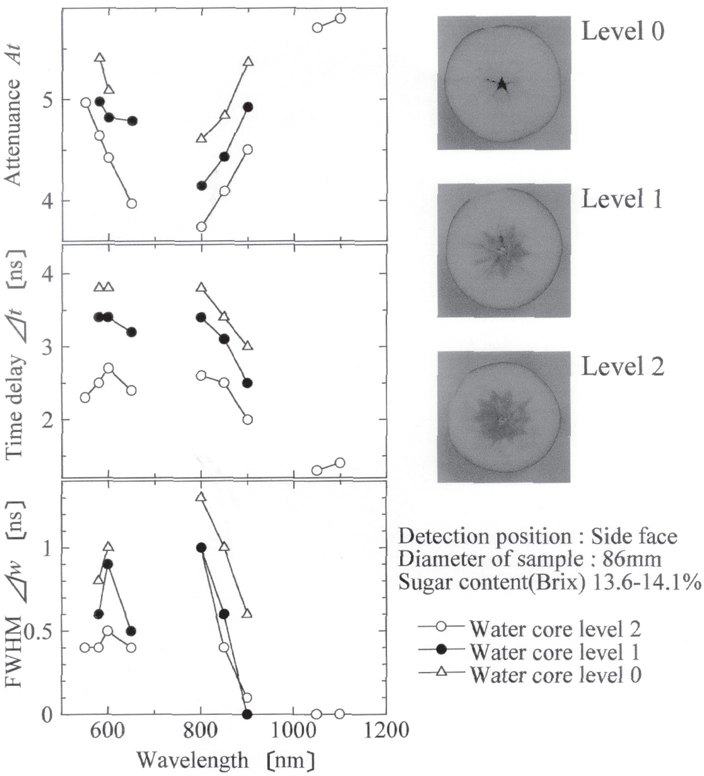

Figure 2. Spectral variation of the attenuance *At*, the time delay of peak maxima Δt and the variation of full width at half maximum Δw.

Results and discussion

Variation of time-resolved profile with water core

Figure 2 indicates the spectral variation of A_t, Δt, and Δw with the presence and level of the water core, respectively. In visual evaluation, we used a scale of "level 0" for a sound apple to "level 2" for apples having solid water core.

It is known that, independently, A_t decreases gradually as the size of the water core increases. In the presence of water-cored tissue (level 2), we could find an output signal at around 1000 nm which may be assigned to water absorption; however, other samples had no data because of a strongly attenuated output signal. This means that the water-cored tissue would transmit much more energy.

Δt and Δw also decrease gradually as the size of the water core increases; however, its wavelength dependency is inversely related to A_t. When the size of the water core increases, the intercellular spaces are filled with liquid, or the cells have become swelled, eliminating air spaces which results in a translucent or water-soaked appearance. This results in less light scattering, so that the light path time through a sample decreases.

Variation of A_t, Δt, and Δw with sugar content

We examined the variation of A_t, Δt, and Δw with sugar content. Figure 3 shows the relationship between the sugar content and each optical parameter normalised by diameter. The wavelength of the laser beam was $\lambda = 850$ nm and the output detected at directly opposite the irradiation position.

A_t/d, $\Delta t/d$ and $\Delta w/d$ decreased gradually as the water core increased. Such a tendency was noticeable in water-cored apples. As shown in Figure 3(c), sugar content is correlated with the normalised Δw independently of water-cored condition. To correctly interpret these results, we may consider that the difference in the refractive index between the cellular structure and the intercellular spaces of an apple differ with the condition of water core. It is known that the refractive index of the cellular structure may approach those of the intercellular spaces as water core increases. So, we know that the variations of the refractive index with the water core or sugar content relates directly to the time-resolved profiles. In any optical parameters, apples with water core have a higher correlation coefficient than those without water core.

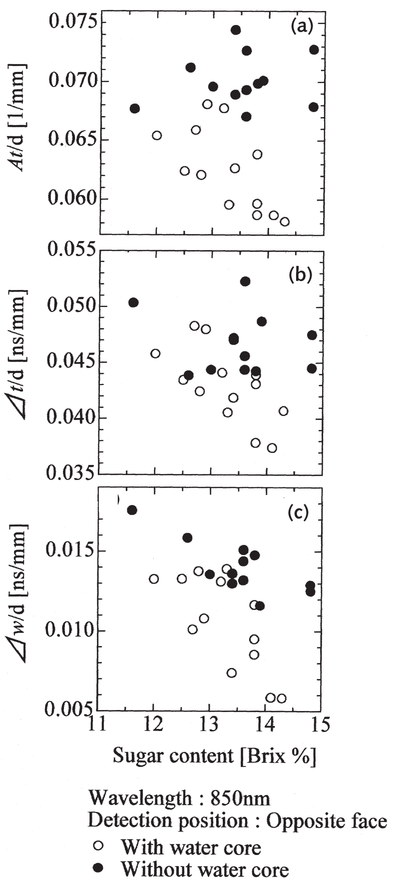

Figure 3. Relationship between sugar content and each normalised parameter.

Conclusions

An optical measurement system, which was mainly composed of a parametric tunable laser and a near infrared photoelectric multiplier, was introduced to detect inner information of apples using time-of-flight near infrared spectroscopy (ToF-NIR). The combined effects of the condition of water core, the sugar content and the sample diameter on the time-resolved profiles were investigated in detail. The attenuance of peak maxima At, the time delay of peak maxima Δt and the variation of full width at half maximum Δw decreased gradually as the water core increased. The water-cored tissue would transmit much more energy because of the filling of the intercellular spaces of an apple with liquid, so that the light path time through a sample decreased. These optical parameters were also governed by the wavelength dependency of light scattering and absorption characteristics. It became clear that At, Δt and Δw decreased as the sugar content increased. Such a tendency was noticeable in water-cored apples. The variations of the refractive index with the water core or sugar content relates directly to the time-resolved profiles. Thus, we can know the sugar content by measuring the optical parameters.

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