Development of a Non-invasive System to Measure the Thickness of the Subcutaneous Adipose Tissue Layer for Human

Hyuck Ki Hong, Young Chang Jo, Yeon Shik Choi, Beom Joon Kim*, Hyo Derk Park

Abstract**—**To measure the thickness of the subcutaneous adipose tissue layer, a non-invasive optical measurement system (λ=1300 nm) is introduced. Animal and human subjects are used for the experiments. The results of human subjects are compared with the data of ultrasound device measurements, and a high correlation (r=0.94 for n=11) is observed. There are two modes in the corresponding signals measured by the optical system, which can be explained by two-layered and three-layered tissue models. If the target tissue is thinner than the critical thickness, detected data using diffuse reflectance method follow the three-layered tissue model, so the data increase as the thickness increases. On the other hand, if the target tissue is thicker than the critical thickness, the data follow the two-layered tissue model, so they decrease as the thickness increases.

Keywords**—**Subcutaneous adipose tissue layer, non-invasive measurement system, two-layered and three-layered tissue models.

I. Introduction

MEASURING the thickness of hypodermis including the subcutaneous fat layer is important in several fields including global assessment of nutritional status, monitoring of dietary manipulation, post operative evaluation of liposuction. It also provides useful information concerning the amount of peripheral adipose tissues and can be used as an index of peripheral obesity. It is necessary to develop a system to measure the thickness of the subcutaneous adipose tissue layer in a precise, quick and simple way for daily use. There are several techniques to measure the thickness of subcutaneous adipose tissue *in vivo* like skinfold caliper (1), computerized tomography (2, 3, 4, 5), ultrasound measurement (6, 7) and optical measurement technique using visible wavelength range (8). But these techniques have limitations (9, 10, 11, 12) for daily use. The optical measurement technique using near infrared determines the thickness of the subcutaneous adipose tissue layer. It measures the thickness using optical properties of skin tissue layers: the skin layer, the adipose tissue layer and the muscle layer. To measure the thickness of adipose tissue, the two-layered tissue model and the three-layered tissue model are introduced. They are very successful in explaining the result of animal experiments and human experiments. This system can provide a rapid, safe, non-invasive technique for nutritional assessment and body composition measurement so that it may be applicable in many practical and clinical fields.

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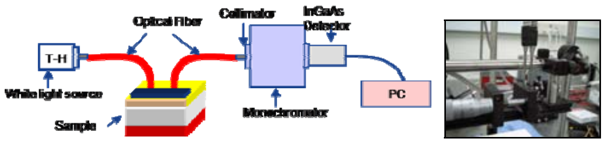
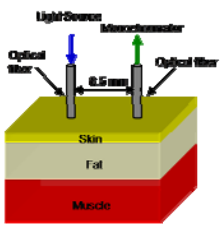
II. Methods

A. Experimental setup and apparatus

In order to measure the thickness of subcutaneous adipose tissue, a diffuse/reflectance measurement system and a sensor probe type system were used (Fig. 1).



(a)



(b)

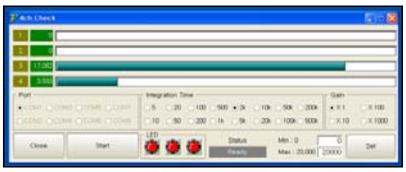
Fig. 1 Subcutaneous adipose tissue measurement system (a) Diffuse reflectance measurement system and (b) Schematic of the tissue experimental set-up

To measure corresponding signal changes depending on the change of the thickness of subcutaneous adipose tissue, the diffuse/reflectance measurement system in Fig. 1 (a) was used. A tungsten lamp (66180, ORIEL, USA) with a full wavelength spectrum was used as a light source. A monochromator (DM202, DongWoo Optron Co. Ltd., KOREA) was used to make monochrome rays. An InGaAs photo detector (IGA030-TE2-H, Electro Optical Systems INC., USA) and a

TE-cooler (PS/TC-1, Optical Systems INC., USA) were used as a detection system. Monochrome rays from the monochromator reached the skin layer via an optical fiber. The diffuse/reflected light from the sample was collected and sent to the detection system via another optical fiber. The distance between the two optical fibers was fixed at 8.5 and the core size was 1 mm in both.

The optical measuring system to measure the thickness of subcutaneous adipose tissue is consisted of three parts: a sensor head, a control board and a data process part. The sensor head has three light emitting diodes (λ=1300 nm) and two InGaAs photo diodes. It has a circular shape (φ = 40 mm) and the dimension is relatively large to have no special sensor for the pressure during measurement. The plane that contacts the skin has two parts of different heights. The outer part is higher than the inner part, so light from outside is blocked during measurement. Light from the three light emitting diodes penetrates into the skin and it is reflected, diffused and absorbed. After the reaction, the InGaAs photo diode measures the intensity of light. The operating circuit is consisted of three units: a sensor probe unit, a signal processing unit and a PC communication unit (Fig. 2 (c)).

(a)



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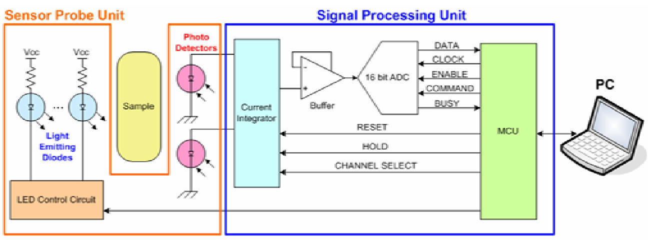


(c)

Fig. 2 (a) A sensor probe type system, (b) the operating program and (c) the system block diagram

The 16bit ADC (Analog to Digital Converter) in the signal processing unit converts the measured analog signal to digital number. The light emitting diodes and photodiodes are controlled by a MCU (Micro Controller Unit) which communicates with a personal computer via a RS-232C port. The control program has four detector channels, 16 steps of integration time and 4 steps of gain controller. An ultrasound device with a 10 MHz transducer (Philips, HDI 3500, Netherlands) was used to calibrate and evaluate the optical system for human. To measure skin thickness, a high frequency B-scan ultrasonic scanner with a 20MHz transducer (CORTEX Technology, DermaScan C, Denmark) was used.

B. Sample

Three layers of tissue were prepared by skin biopsies for animal experiments: the epidermal and dermal layer, the subcutaneous adipose tissue layer, and the muscle layer. Among these three layers, the muscle layer was separated from a mass of epidermis, dermis, and adipose tissue layers. The tissue sample had a rectangular parallelepiped shape and was taken from the sirloin part of pork. The dimension of the top square is 50 mm × 50 mm and the thickness varied between 19 mm and 39 mm according to the thickness of the adipose tissue layer. The thickness of the adipose tissue layer varied between 0 mm to 20 mm, while the thicknesses of the skin layer and the muscle layer were fixed at 4 mm and 15 mm, respectively. The mass of muscle was located at the bottom of the mass of skin and adipose tissue layers. The adipose tissue layer was cut by 2 mm after every measurement using a specially designed cutting tool.

To compare the different techniques to measure the thickness of subcutaneous adipose tissue, namely, between the optical measuring system and the ultrasound device, we measured 18 healthy women and 3 healthy men. Characteristics of the subjects are summarized in Table 1.

TABLE I CHARACTERISTICS OF HEALTHY SUBJECTS (MEAN □ SD, RANGE)

Group	Number of Sample	Age (yr)	Height (cm)	Weight (kg)
Women	18	28.4 ± 4.8 (24-37)	159.5 ± 4.9 (154-169)	56.3 ± 4.6 (49-63)
Men	3	29.7 ± 4.5 (25-34)	179 ± 5.6 (173-184)	71.7 ± 10.6 (62-83)

Tissue images obtained from the ultrasound device could be classified into four layers: the epidermis and dermis layer, the superficial subcutaneous adipose tissue layer, the deep subcutaneous adipose tissue layer and the muscle layer. Anatomical and morphological examination of the subcutaneous adipose tissue depot led to the identification of two distinct compartments within the subcutaneous anatomical region: a superficial layer of adipose tissue evenly distributed under the dermis of abdominal skin; and a deeper subcutaneous adipose tissue compartment located under the superficial adipose tissue layer. The superficial adipose layer is contained within organized compact fascial septa (12). Each of the superficial and deep subcutaneous adipose tissue areas represented ~50% of the total subcutaneous area (13). The data from the optical measuring system stand for the thickness of the superficial adipose tissue layer, and the thickness of the subcutaneous adipose tissue layer can be represented by the superficial adipose tissue layer. Thus, in this work, the data of the optical measuring system stand for the thickness of subcutaneous adipose tissue. Measurement was made using both devices on the abdomen 5 cm by the umbilicus.

Measurement was made five times to obtain the average signal amplitude. The skin thickness at the same site was measured to study the effect of the skin layer.

C. Animal experiments

To measure the corresponding signal changes depending on the changes of the thickness of the subcutaneous adipose tissue layer, experiments were performed as follows. A mass of the muscle layer and a mass of the skin and subcutaneous adipose tissue layer were prepared. The mass of muscle was located under the bottom of the mass of the skin and adipose tissue layers. The adipose tissue layer was cut by 2 mm after every measurement using a specially designed cutting tool. Samples were measured at 350 points in the range from 1000 nm to 1700 nm.

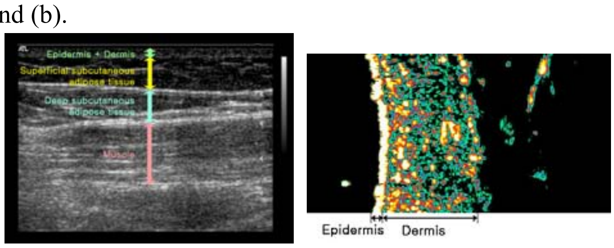
D. Human experiments

The thicknesses of subcutaneous adipose tissue were measured in order of the following protocol: an optical measuring system and an ultrasound device with a 10 MHz transducer to measure the thickness of the adipose tissue layer and an ultrasound device with a 20 MHz transducer to measure the skin layer. The targeted site was marked after measurement with the optical measuring system because a mark on the skin could affect the optical method. Measurement using the ultrasound device with a 10 MHz transducer was performed under constant pressure in order to use the measured data as a control group. After the measurement, the thickness of the same site was measured using the ultrasound device with a 20 MHz transducer. Each of twenty one subjects was measured using the three different devices.

III. Results

A. Non-invasive measurement system

Abdominal skin is composed of epidermis, dermis, and subcutaneous adipose tissue, and beneath it is the muscle layer. These layers have different optical properties, which can be used to measure the thickness of subcutaneous adipose tissue *in vivo*. Human skin images taken with the ultrasound device with a 10 MHz and a 20 MHz transducer are depicted in Fig. 3 (a) and (b).



(a) (b)

Fig. 3 (a) An image of the ultrasound device with a 10 MHz transducer and (b) an image of the ultrasound device with a 20 MHz transducer for the skin thickness measurement

Anthropometric characteristics of the subjects are shown in Table 2. The mean skin thickness is 2.102±0.2041 mm and the range is from 1.798 to 2.474 mm. The mean thickness of superficial subcutaneous adipose tissue is 10.416±0.4133 mm and the range is from 1.38 to 17.41 mm.

TABLE II ANTHROPOMETRIC CHARACTERISTICS OF THE SUBJECTS

Variable	Mean ± SD	Range
Skin Thickness (mm)	2.102 ± 0.2041	1.798 – 2.474
Superficial subcutaneous adipose tissue thickness (mm)	10.416 ± 0.4133	1.38 – 10.74
Photodetector signal value (a.u.)	29275.7 ± 2934.1	22004.7 – 35073.8

B. Two-layered and three-layered tissue model

Light propagation in tissue can be explained by modified Beer's law and expressed by the following equation on the assumption that the layers are uniform in material and thickness

$$I = I_0 \sum \exp(-\alpha_1 x_{1i}) + I_0 \sum \exp(-\alpha_1 y_{1i}) \cdot \sum \exp(-\alpha_2 x_{2j}) + I_0 \sum \exp(-\alpha_1 y_{1i}) \cdot \sum \exp(-\alpha_2 y_{2j}) \cdot \sum \exp(-\alpha_3 x_{3k}) \quad (1)$$

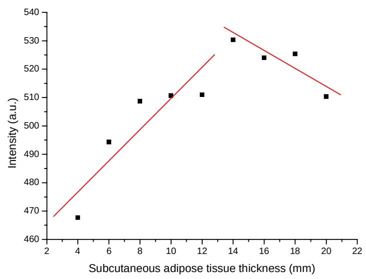
where I is detected light intensity, I_0 is incident light intensity, α_n is absorption coefficient, x_n and y_n are variables representing the source-detector distance and the thickness of each layer, respectively. Subscripts i, j and k represent the pathways, through which the incident light passes through in each layer. Layer 1, 2 and 3 represent the skin layer, the adipose tissue layer and the muscle layer, respectively. The influence of layer 1 on layer 2 is constant and the equation can be simplified as follows

$$I = C_1 + I_0' \sum \exp(-\alpha_2 x_{2j}) + I_0'' \sum \exp(-\alpha_3 x_{3k}) \quad (2),$$

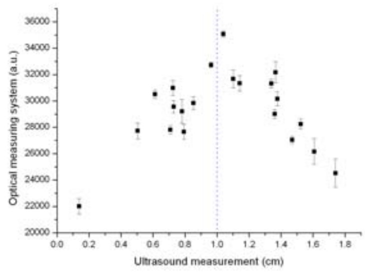
where I_0' and I_0'' are incident light to layer 2 and 3, respectively. There are two models depending on the incident light intensity: the two-layered model and the three-layered model. If the incident light intensity is sufficiently high to reach the muscle layer, it follows the three-layered tissue model, and if it is not, it follows the two-layered tissue model. In the three-layered tissue model, x_{2j} and α_3 are the main factors that influence I. The incident light is affected by x_{2j} the thickness of layer 2 until the light meets layer 3, and after it meets layer 3 it is almost absorbed by light α_3. In other words, the amount of light in layer 2 decides detected light I. Thus, I increases as the thickness increases. In the two-layered tissue model, I is not affected by layer 3. The increase of the thickness of layer 2 means the increase of the path length in the equation of Beer's law. That means that the detected light decreases as the thickness of layer 2 increases. Therefore the light intensity decides the critical thickness that determines the tissue model between the three-layered and two-layered models.

C. Human experiments

According to the three-layered tissue model, the detected signal using the optical measurement system increases as the thickness of subcutaneous adipose tissue increases if the subcutaneous adipose tissue is thinner than the critical thickness. On the other hand, if it is thicker than the critical thickness, the detected signal decreases as the thickness increases by the two-layered tissue model. These models explain two trends in the animal experiment (Fig. 4 (a)) and in the human experiment (Fig. 4 (b)).



(a)



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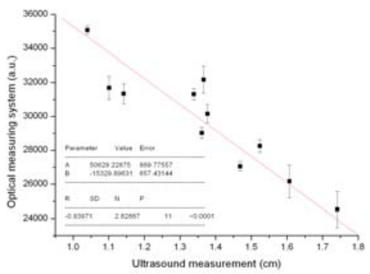

(c)

Fig. 4 (a) Comparison of the subcutaneous adipose tissue thickness of animal samples measured by the diffuse reflectance measurement system and the actual thickness. The red lines indicate two different tissue models. (b) Comparison of the superficial subcutaneous adipose tissue thickness at the human abdomen site measured by the optical measuring system and the ultrasound device. A dotted line in center indicates the critical thickness which makes the tissue model change. (c) Calibration curve of (b) in the range over 10 mm of thickness (n = 11, r = 0.94)

The data measured by the optical system were compared with the actual thickness of animal samples and the red lines in Fig. 4 (a) indicate the two different tissue models. In this experimental condition, the tissue model was changed at thickness of 13 mm. In Fig. 4 (b), the signal increases in thickness range of 1-10 mm, and it follows the three-layered tissue model, and data in the range of 10-18 mm follow the two-layered tissue model. The critical thickness in this work is about 10 mm based on the optical power with three light emitting diodes. If more powerful light is used as the light source, the critical thickness would be moved to the thicker direction. In Fig. 4 (c), the values of the optical measuring system and the ultrasound device are strongly correlated with each other (r=0.94 for n=11) with linear regression of y = 50629.22 – 1532.989x (SD = 2.83). The available measuring range is up to about 18 mm in Fig. 4 (c). Considering that the data represent the thickness of the superficial subcutaneous adipose tissue, thickness of 18 mm means that the total subcutaneous adipose tissue is 36 mm thick. With the optical power used in this experiment, it is expected to extend the measuring range up to about 30 mm, which is about 60 mm in terms of total thickness.

The thickness of the skin has an influence on the signal gained from the optical measurement system. Skin thickness is expected to be measured by the relationship between photodetectors placed at different distances from the light source and it will be explored in future study

IV. Discussion

To measure the thickness of the subcutaneous adipose tissue layer, two-layered and three-layered tissue models were introduced. If the thickness of the subcutaneous adipose tissue is thinner than the critical thickness, signal detected using the diffuse reflectance method follows the three-layered tissue model. Thus the data increase as the thickness increases. On the other hand, if it is thicker than the critical thickness, the signal follows the two-layered tissue model, so they decrease as the thickness increases. The results of animal and human experiments were explained well by these models. For the human experiments, the optical measurement system and the ultrasound device were highly correlated with each other (r=0.94 for n=11). Although the thickness of skin layer affects in the diffuse reflectance data, it has not been studied yet. It will be studied in future work using detectors located at different distances from the light source. Although direct skin biopsies with tissue image analyzer or light microscopy provide exact mean thickness of human skin including epidermis, dermis, and subcutaneous tissue layer, it is scarcely performed in the practical fields due to its invasiveness and remaining scars. On the other hand, non-invasive devices for measuring skin thickness are too expensive or suspicious of their precision and validities. This newly developed optical non-invasive system for measuring skin thickness might be applied in many fields such as post-operative evaluation of liposuction, endocrinology, dermatology concerning regional local obesities, and various cosmetic researches.

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