Method for Estimation of Structural Composition of Skin Layers based on Light Propagation Simulation for Liposuction Applications

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***Abstract*—Skin surface irregularity is the most common side effect after liposuction. To reduce this, it is necessary to devise a systematic method to provide structural composition details of skin layers, such as fat thickness and fat boundary tilt angle, for the plastic surgeon.**

Several commercial portable devices are available to measure skin layer information, working on the principle of a near-infrared technique using the light penetration properties of tissue in optical windows. However, these can only measure general fat thickness and not the structural compositions of skin layers with irregularities. Therefore, our goal in this paper is to propose a method to estimate the structural compositions of skin layers by analyzing and validating the relationship between light distribution and structural composition from simulation data based on specific structural conditions.

I. Introduction

Liposuction is reported to be the most popular plastic surgery procedure in the world [1]. However, it has various side effects and complications. The most common and serious side effect is skin surface irregularity caused by uneven and irregular fat removal from skin layers, which is dependent on the surgeon's skill [2]. At present, the only method available to check the structural composition of a fat layer is the sense of touch of the surgeon's hand.

In the biomedical optics field there are portable devices for fat thickness estimation but these do not provide enough information to reduce the skin surface irregularity caused by liposuction. Therefore, in this paper, we propose a method to estimate the structural compositions (fat thickness and boundary tilt angle, shown in Fig. 1) from the light distribution on the skin surface by improving the method used to estimate structural composition information.

To improve the method used for skin layer structural composition estimation, it is necessary to extract parameters to act as indicators from the light distribution. Accordingly, in this paper, we perform analyses to extract parameters that clearly indicate the relationship between the structural composition of, and the light distribution on, skin layers. In our previous papers [3][4], we proposed two methods based on Monte Carlo simulations to consider light propagation from a radial beam light-emitting diode (LED) in multilayers with a tilted boundary. We acquired simulated data using the proposed methods and analyzed the data to determine the relationship between light distribution and structural composition as a method to estimate fat thickness and the fat boundary tilt angle. We then verified the relationship using the simulated light distribution and experimental data based on adjustments of the fat thickness and the boundary tilt angle.

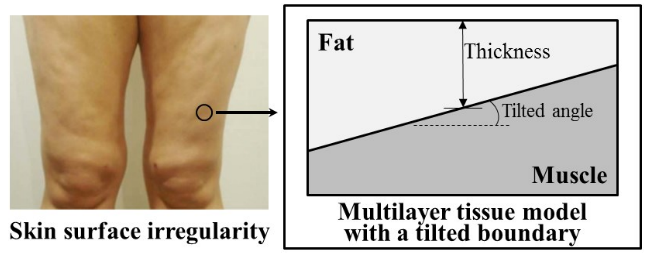

Figure 1. Multilayer tissue model with tilted boundary from skin surface irregularity caused by liposuction

II. Simulation

The simulation methods used for this research have been suggested previously by the authors: simulation of light propagation with consideration of radial beam LED properties [3], and light propagation simulation of multilayers with a tilted boundary [4]. Here, we briefly describe the aims of each simulation.

A. *Simulation of Light Propagation with Consideration of Radial Beam LED Properties*

To check the structural compositions of broad surfaces in skin layers, it is more effective to use a radial beam source than a laser source because light from laser sources interacts with narrow surfaces. Therefore, we selected a radial beam LED as the light source. For the simulation, we consider the light source characteristics as follows:

- *it is not possible to assume the LED to be a point light source (initial launch area);*
- *the radial beam LED has very wide light radiation angles at the initial launch area (radiation angle);*
- *the round shape of the head means that the LED does not entirely make contact with the tissue (refraction according to the contacted area).*

To apply these characteristics in the simulation, we built the initializing photon step, as shown in Fig. 2.

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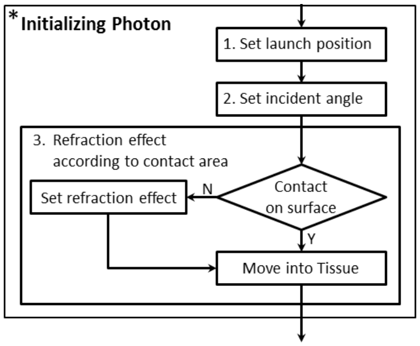


Figure 2. Flowchart for initializing photon from radial beam LED source.

B. Light Propagation Simulation on Multilayers with Tilted Boundary

To determine the relationship between the skin layer compositions and the light distributions on these layers, we must simulate light propagation on multilayers with a tilted boundary. To apply a tilted boundary to the light propagation simulation we configured a boundary plane equation. The transformation matrix

$$\mathbf{T} = \begin{bmatrix} a^2(1-\cos\theta_l)+\cos\theta_l & ab(1-\cos\theta_l)-c\sin\theta_l & ac(1-\cos\theta_l)+b\sin\theta_l \\ ab(1-\cos\theta_l)+c\sin\theta_l & b^2(1-\cos\theta_l)+\cos\theta_l & bc(1-\cos\theta_l)-a\sin\theta_l \\ ac(1-\cos\theta_l)-b\sin\theta_l & bc(1-\cos\theta_l)+a\sin\theta_l & c^2(1-\cos\theta_l)+\cos\theta_l \end{bmatrix}$$
$$a=\sin\theta_l\cos\phi_l,\; b=\sin\theta_l\sin\phi_l,\; c=\cos\theta_l \quad (1)$$

is generated before the photon is initialized. The transformation is used selectively where applicable in the

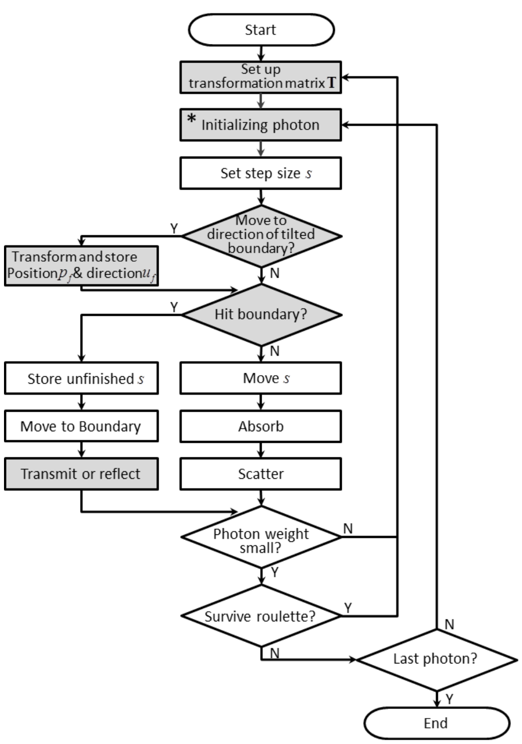


Figure 3. Flowchart of the proposed simulation; gray steps differ from the existing simulations; the asterisked (*) step is for consideration

simulation (transform and store position p_f and direction u_f in Fig. 3.) when the tilted boundary interaction calculations are performed.

III. Analysis for Parameter Extraction for Structural Composition Estimation of Skin Layer

To estimate the skin layer structural composition from light distributions on the skin layer surfaces during liposuction, it is necessary to acquire the relationship using parameters extracted as indicators from the light distribution. In this section, we perform an analysis to extract the parameters that clearly show the relationships of the structural composition in skin layers: the fat thickness and the boundary tilt angle.

We acquired simulation data by the method proposed above under the conditions in Tables I. We then analyzed the data to determine parameters for structural composition estimation of surface irregularities in skin layers using the procedure shown in Fig. 4.

TABLE I. Simulation Setting

Light Source		
Dimensions ϕ [mm]	5	
Dominant Wavelength [nm]	940	
Radiation Angle (Half-value) [deg]	±30	
Optical Properties of Skin Layers		
	Fat layer	Muscle layer
Refractive Index n	1.4	1.4
Absorption Coeff. μ_a [cm^{-1}]	0.25	6.0
Reduced Scattering Coeff. μ_s' [cm^{-1}]	10.0	5.0
Anisotropic Factor g	0.9	0.9
Structural Composition		
	Thickness[mm]	Boundary angle [deg]
Min. Value	8.0	0.0
Max. Value	18.0	35.0
Interval	1.0	5.0

Threshold: We used images from a camera with a near-infrared (NIR) pass filter as experimental data to verify the result. However, the simulation data derived by the proposed method are only a set of relative intensities that cannot be considered for comparison with the experimental data. Therefore, we must first consider the simulation data as verification of the experimental data. The experimental data have a sensed light intensity range that is limited by the camera's image sensor specifications. Therefore, the rate of light intensity change on the NIR image is recorded in a set light intensity range. Where the light intensity is outside the set range, it is measured as a saturated value at upper and lower thresholds based on the maximum and minimum sensing ranges, respectively. To consider this property for the simulated data, we assume a threshold value in the simulation

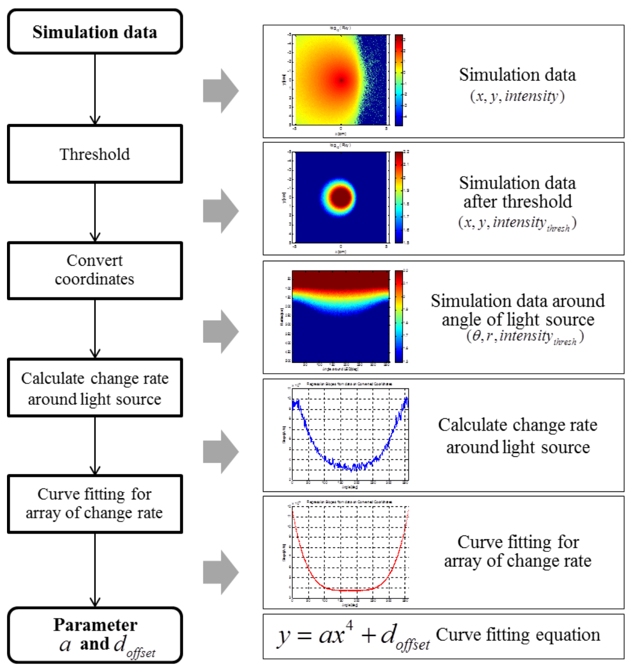
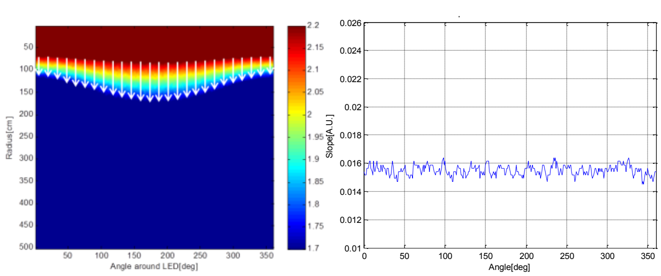


Figure 4. Flowchart for parameter extraction.

data for saturation based on the upper and lower thresholds of the experimental data. From studying the light intensities of the experimental data, we configured a lower threshold of 1.7 and an upper threshold of 2.2 for the simulation data.

Conversion of coordinates: To observe the change in light propagation based on the structural composition of the skin layers more clearly, we converted the simulation data from positions x and y in Cartesian coordinates to an angle θ around the light source and a radius r centered at the light source position. The light distribution in the converted coordinates allows us to observe light propagation trends more clearly.

Calculation of change rate around light source: In this step, light intensity change rates are calculated to quantify changes in the light distribution, depending on the structural composition configuration in the converted coordinates. Fig. 5 shows the simulation data in the converted coordinates. If the tilt angle increases, the distribution in the Cartesian coordinates is biased to one side, where the perpendicular distance from the skin surface to the boundary is higher.



(a) (b)

Figure 5. Light distribution change rate from simulation data; fat thickness of 9 mm, boundary tilt angle of 0°, (a) light distribution in the converted coordinates (White arrow: calculation direction for change rate), (b) calculated change rate

Therefore, using the coordinates based on radius and angle around the light source as the converted coordinates, the data are expressed as per the right side of the figure. To quantify the structural composition-dependent change in the light distribution, and especially the tilt angle, we calculated the change in the rate inside the band marked by the white arrow in Fig. 5. In the figure, the direction of the white arrows shows the positive direction for calculation of the change rate.

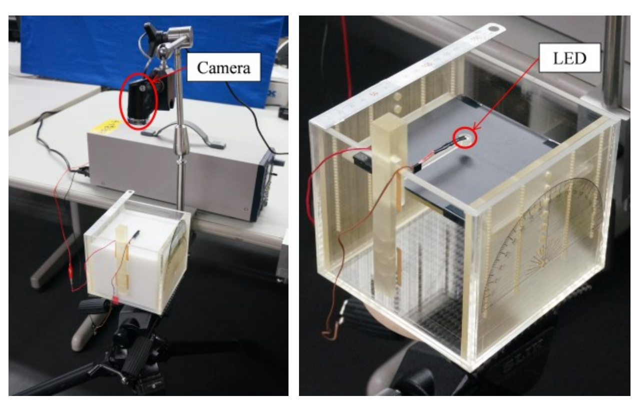
Curve fitting for array of change rate: It is reasonable to use the coefficient and offset of a curve at the change rate in the converted coordinates as an indicator because the change rate pattern is clearly seen to depend on the structural composition of the skin layers. In this step, we extracted indicators from the sets of change rates to estimate the structural composition: the fat thickness and the boundary tilt angle. For that, we performed curve-fitting analysis from the light propagation change rate set. The equation applied for curve-fitting analysis is

$$y = ax^4 + d_{offset}. \quad (2)$$

The equation was empirically selected after observation of the data pattern (a : gradient of change rate, d_{offset}: offset of change rate). Among several equations tested by the authors, this fourth order polynomial was most appropriate in terms of parameter numbers, fitness and expressivity as an indicator for the estimation.

IV. Verification

We verified the relationship between extracted parameters a and d_{offset} and the skin layer structural compositions from the simulation experimentally (Fig. 6). The analysis method used to extract the parameters required two-dimensional light diffusion data on the skin surface as input data. Therefore, the skin surface light distribution data was measured by the camera with the NIR pass filter. The experimental conditions, including the camera and the NIR pass filter properties, are described in Tables II and Fig. 7 shows the relationships between parameters and structural compositions from simulated and experimental data. The correlation coefficients used for verification are given in Table III.



(a) (b)

Figure 6. Measurement setup
(a) Camera location, and (b) LED location (without phantoms)

TABLE II. EXPERIMENTAL SETTINGS - LED SPECIFICATION

LED Specification	
LED Type	GaAlAs/GaAs
Head Type	Round plastic
Dimension ϕ [mm]	5
Dominant Wavelength [nm]	940
Radiation Angle (Half-value) [deg]	±30
Camera Specification	
Resolution	1920×1080
Sensor Type	Full HD CMOS
Lens	F2.0 mm f=3.0 mm
Min. Intensity of Illumination	10 lux
NIR Pass Filter Specification	
Filter Type	Infrared Sharp Cut
Material	Triacetyl cellulose
Dominant Wavelength [nm]	940
Thickness [µm]	185±15

TABLE III. CORRELATION COEFFICIENTS BETWEEN SIMULATED AND EXPERIMENTAL DATA

	Parameter a	Parameter d_{offset}
Correlation Coefficient	0.9871	0. 9119

V. CONCLUSION

The correlation coefficients show that a and d_{offset} have strong correlations with the tilt angle and the fat thickness. We conclude that these parameters and this method are sufficient for structural composition estimation.

However, in the case of the extracted d_{offset}, there is lower correlation with the structural condition of the skin layers. The reason for this lower correlation is the high sensitivity of the environmental configurations and an artifacts effect from the part of the NIR image that is blocked by the LED support fixture.

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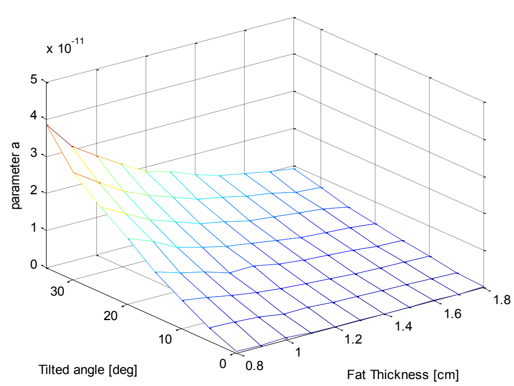
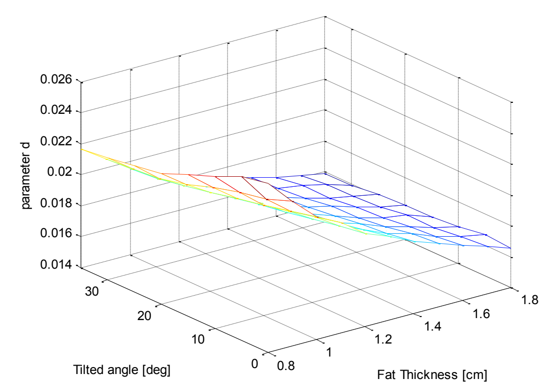
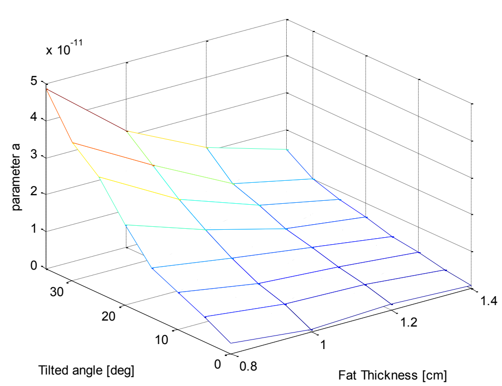


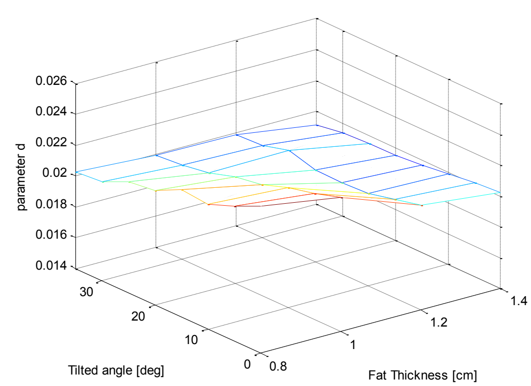
(a) Parameter a from simulated data.



(b) Parameter d_{offset} from simulated data.



(c) Parameter a from experimental data.



(d) Parameter d_{offset} from experimental data.

Figure 7. Relationships of parameters a and d_{offset} from simulated data and experimental data to the structural conditions of skin layers.