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Functional illumination supporting the visual detection of plaques

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Abstract

Some people often suffer from periodontal diseases and poor oral environments can be the cause of such diseases. The maintenance of oral health is a crucial issue for general health. One of the measures to maintain oral health is by brushing teeth to remove plaque. However, it is difficult to remove plaque perfectly because the color of plaque is similar to the color of the teeth making it difficult to find remaining plaque by simple visual inspection. In this study, we propose a functional illumination that helps detecting plaque on teeth. The functional illumination was optimized to enhance the color difference between the plaque and the teeth in a CIELAB color space. We designed the spectrum of the illumination by NLP (Non Linear Programming) in such a way that the color difference between the teeth and the plaque is maximized. The optimized illumination has a peak at 420 nm because the largest difference is observed in the reflectance between the teeth and the plaque in this wavelength. The color difference increased with the functional illumination by a factor of 3 with respect to a normal white light source. Additionally, we implemented the real functional illumination by a combination of LEDs and it was able to enhance color discrimination. For different participants, the functional illumination could also enhance color discrimination.

Introduction

Periodontal disease is the most common chronic infection in adults. A poor oral health condition can be the cause of such oral disease including cavities. Additionally, oral infection, especially periodontitis, may cause a number of systemic diseases, such as cardiovascular disease, bacterial pneumonia, diabetes mellitus, and low birth weight [1, 2]. Therefore, maintaining a good level of oral health is essential for general health. Diet and dirt (hygiene), smoking, alcohol, risky behaviours causing injuries, and stress are known as risk factors of oral disease [3]. In addition to avoiding these risk factors, brushing teeth is effective in maintaining oral health. Brushing teeth can remove dirt including plaque. However, we cannot remove plaque perfectly by brushing and it is difficult to visually check the remaining plaque because the color of plaque is similar to the color of teeth. For visual plaque detection, we can use plaque disclosing agents. These agents discolor plaque to a red color by an agent liquid. That is helpful to visually check the remaining plaque. However, the agent liquid dyes the oral cavity, thus the user needs to rinse the liquid after the visual check for plaque.

This study proposes a new system using a functional illumination for supporting visual detection of plaque. The functional illumination changes the color appearance of the plaque. The basic idea of the functional illumination has been proposed by Nakauchi et al. [4] and Ito et al. [5]. The functional illuminations in their study were composed of LEDs (Light Emission Diodes) which enables us to design various illumination spectra because an LED has a narrow band in its illumination spectrum. In their studies, the functional illuminations are found as a combination of three types of LEDs which have different spectra. The candidates of the combination are all combinations of available LEDs that satisfy some constraints. For the constraints, "the resulting illumination is white" or "the resulting illumination does not change the color of a certain materials" have been used. These constraints, where the illumination changes one of the target materials but does not change the other, utilize the metamerism effect. The metamerism effect is a phenomenon occurring in human vision where the colors of some materials match even though their reflected spectra are different. This phenomenon is caused by a characteristic of the human eye which compresses spectral information into three trisimulus values [6] or cone-excitation responses, known as univariance.

In this study, we propose a functional illumination based on previous studies [4, 5]. Moreover, a new method for design of the illumination spectrum is also proposed because the design method used in the previous studies has two problems. The first problem is the computational cost. Because the conventional method adopts a grid-search-based method to find the optimal combination of LEDs, computation is time-consuming. Thus, it is difficult to design an illumination with more than three types of LEDs due to its computational cost. The second problem is the need of the constraint for the illumination color. Although this constraint is needed to obtain all combinations of the LEDs, having the constraint means that the resulting illumination may not produce the "largest" color difference due to the limited parameter space. In order to solve this inefficiency in computation and achieve a constraint-free optimization, we formulate the design process of the functional illumination as a nonlinear optimization problem. The problem can be solved by sequential quadratic programming [7]. This can provide a faster solution than the grid-search-based optimization. Moreover, our approach provides higher flexibility than the previous method because our method does not require any constraints and it can combine more than three types of LEDs. We show the efficiency of the functional illumination designed by the proposed method for plaque detection with a computer simulation and an implemented illumination.

(a) Before brushing (b) With liquid (c) After brushing

Figure 1. Measurement flow to acquire the spectral images

Materials and Methods

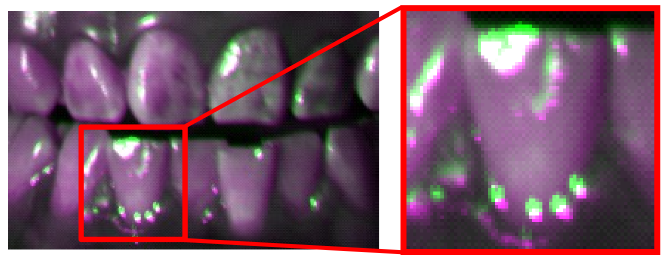
Measurement of reflectance spectra of teeth and plaque

We measured the reflectance spectra of teeth under three different conditions, “before brushing” (the teeth had not been brushed for 24 hours), “with a plaque disclosing agent”, and “after brushing”. The measurement flow is shown in Fig. 1. We used an LCTF (Varispec VIS 10-20, Perkin Elmer) and a monochrome camera (Retiga SRV, QImaging). The spectral range for the measurements was from 400 to 720 nm with 5 nm intervals (λ = 400, 405, … , 720). The discrete indexes for the wavelength of λ are denoted by l (l = 1, … , 65). The exposure time for each filter was adjusted such that the intensity of the camera response level of a white patch adjacent to the teeth was 85% of the saturation level of the camera. We focused for the 560 nm band (center of measurement wavelength). The three conditions were measured by the same environment and the teeth were dried before each measurement to avoid saturated pixels in the spectral images.

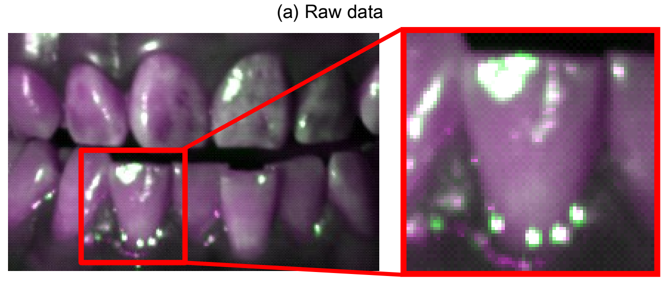
For solving misalignments across the spectrum images captured using the different bands, an image registration method was applied. In this study, we used the feature-based registration method [8]. The feature-based registration method is composed of the following four steps [9, 10]:

1. Feature extraction: The salient and distinctive features (closed-boundary regions, edges, contours, line intersections, corners, etc.) are extracted from two images which needs to solve displacements, the reference and sensed images. More than features, pixels or regions from where these features are extracted are called control points.
2. Feature matching: A set of corresponding control points between the extracted features in step 1 is given. This matching is based on the similarities of their attributes such as size and shape.
3. Transform function estimation: The type and its parameters of mapping functions are estimated. The parameters of the mapping functions are calculated by means of the tie points from the corresponding matched features.
4. Image re-sampling and transformation: The sensed image is transformed by the similarity transformation function.

In this study, all spectral images for all conditions were registered based on the image at a 560 nm wavelength because we focused in 560 nm to measure the spectral image. As a example, the result of the registration between the spectral image of 560 nm and 400 nm are shown in Fig. 2. Figure 2 illustrates the difference of the position between the two images. Gray regions in the composite image show regions where the two images have the same intensities. Magenta and green regions show regions where the intensities are different. The raw image (the upper image) has some green and magenta



(a) Raw data



(b) Registered

Figure 2. *Displacement between spectral image with the filter bands of 400 nm and 560 nm. The upper image is a raw image. The lower image is the image after the registration.*

(a) Before brushing (b) With liquid (c) After brushing

Figure 3. *Selected regions to calculate the reflectances*

regions. After the registration (the lower image), these regions decrease. This result suggests that the displacements are improved by the registration.

Optimization for illumination spectrum

The spectrum of the functional illumination was designed using two sets of the reflectance spectra. A set contained the spectral reflectances in the regions of the teeth with plaque in the “before brushing” condition. The other set contained the spectral reflectances in the region of the teeth without plaque in the “before brushing” condition. The spectra in the set were denoted by $R_{11}[l], \mathrm{R}_{12}[l] \ldots R_{1N_1}[l]$ and $R_{21}[l], \mathrm{R}_{22}[l] \ldots R_{2N_2}[l]$, where $R_{1n}[l]$ is reflectance of teeth, $R_{2n}[l]$ is reflectance of plaque, N_1 is the number of pixels of the tooth regions and N_2 is the number of pixels of the plaque regions. Both the plaque and tooth regions were manually found by using the image in the condition "with the agent liquid". We selected thirteen regions from several teeth. For instance, one of the selected regions is shown in Fig. 3. These reflectances were averaged as

$$\overline{R_1}[l] = \frac{1}{N_1}\sum_{i=1}^{N_1} R_{1i}[l] \tag{1}$$

and

$$\overline{R_2}[l] = \frac{1}{N_2}\sum_{i=1}^{N_2} R_{2i}[l] \tag{2}$$

The proposed functional illumination aims to enhance the color discrimination between two predefined targets by designing the illumination spectrum with several LEDs. To optimize the illumination spectrum, we formulate the optimization process into a nonlinear optimization problem formed in an NLP (nonlinear programming) [11]. NLP is a form of nonlinear optimization problems composed of a nonlinear objective function or constraints. In our problem, the color defined in the CIELAB color space is the objective function to be maximized, because color difference in the CIELAB color space is approximately equal to the perceived color of a human [12]. Consider that N_{LED} types of LEDs for the elements of the functional illumination are given. These LEDs have different illumination spectra denoted by $\{I_{LED_i}[l]\}_{i=1}^{N_{LED}}$. The spectrum of the functional illumination $S[l]$ is formulated by

$$S[l] = \sum_{i=1}^{N_{LED}} I_{LED_i}[l]x_i \tag{3}$$

where $\{x_i\}_{i=1}^{N_{LED}}$ are coefficients to be optimized representing the proportions for the LEDs. The color difference between the two different targets is defined by

$$f(x) = \Delta E_{L^*a^*b^*} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$
$$= \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}, \tag{4}$$

where L_1^*, a_1^* and b_1^* are the CIELAB value of the teeth, L_2^*, a_2^* and b_2^* are the CIELAB value of the plaque defined by

$$\begin{bmatrix} L_k^* \\ a_k^* \\ b_k^* \end{bmatrix} = f_{Lab}\left(\begin{bmatrix} \sum_n \overline{R_k}[l]S[l]\bar{x}[l] \\ \sum_n \overline{R_k}[l]S[l]\bar{y}[l] \\ \sum_n \overline{R_k}[l]S[l]\bar{z}[l] \end{bmatrix}\right), \tag{5}$$

where f_{Lab} is the translation function converting XYZ value to the $L^*a^*b^*$ value, and $\bar{x}[l]$, $\bar{y}[l]$ and $\bar{z}[l]$ represent the XYZ color matching functions. Here, reference white is defined as the illumination color because of chromatic adaptation. The optimization problem is

$$max_{\{x_i\}_{i=1}^{N_{LED}}} f(x) \tag{6}$$

$$s.t. f_{XYZ}\left(S[l]_{l=1}^{65}\right) = b, x_i \geq 0, i = 1, \ldots, N_{LED}$$

As the constraints to optimize the spectrum, we set $f_{XYZ}\left(S[l]_{l=1}^{65}\right) = b$, where $f_{XYZ}\left(S[l]_{l=1}^{65}\right)$ is function giving the XYZ color of the illumination and b is an optional XYZ color. This constraint works in such a way that the color of the functional illumination becomes b in the XYZ color space. Although, (6) has the constraint of the illumination color, we do not need to set this constraint. In this case, the optimization problem is represented by

$$max_{\{x_i\}_{i=1}^{N_{LED}}} f(x) \tag{7}$$

$$s.t.\ x_i \geq 0, i = 1, \ldots, N_{LED}$$

For solving the optimization problem in (6) or (7), the SQP (sequential quadratic programming) method can be used [7]. The SQP method solves a sequence of optimization subproblems. Each subproblem optimizes a quadratic model of the objective function with the linearized constraints. The SQP method is proficient at searching the localized solution near the default point or obtaining an optimal solution with relatively high calculation accuracy, and computational cost compared to other global methods [7]. Because of these advantages, we adopted SQP to solve our optimization problem. The algorism of SQP consists of the following six steps.

1. Set a default point.
2. Calculate the gradient in the solution space in the current calculating point.
3. Decide a search direction based on the gradient information.
4. Search a point improving the objective function and satisfying the constraints along the search direction.
5. Move the point.
6. Repeat step2 to 5 until the objective cost converges or the maximum iteration number is reached.

The parameters to implement the SQP method are shown in Table.1.

Table.1 Parameter of the SQP method for our experiment

Parameter	Value
the maximum iteration number	1e6
Maximum number of iterations	1e7
A tolerance (stopping criterion)	1e-20
Permissible errors on XYZ value	1e-6
End tolerance on color difference	1e-6

Results and Discussion

Simulation

Figure 4 shows the spectrum of the designed functional illumination, and the reflectance of the teeth and the plaque. Notably, the largest difference in reflectance is observed at 420 nm. Therefore, the functional illumination has a peak at 420 nm. The color difference between the teeth and the plaque with the functional illumination or white illumination (Diva-Lite, Kino FLO) in each conditions are shown in Table 2. The color differences in all teeth are enhanced by the functional illumination.

A representative of the simulated results is shown in Fig. 5. We can find that the color of the stained regions by the agent liquid is not able to be found by the white illumination. With the functional illumination, those regions become darker than the other regions. This feature cannot be found in the simulation result of the functional illumination in the “after brushing” condition because the plaque in the darker regions had been removed by brushing. In

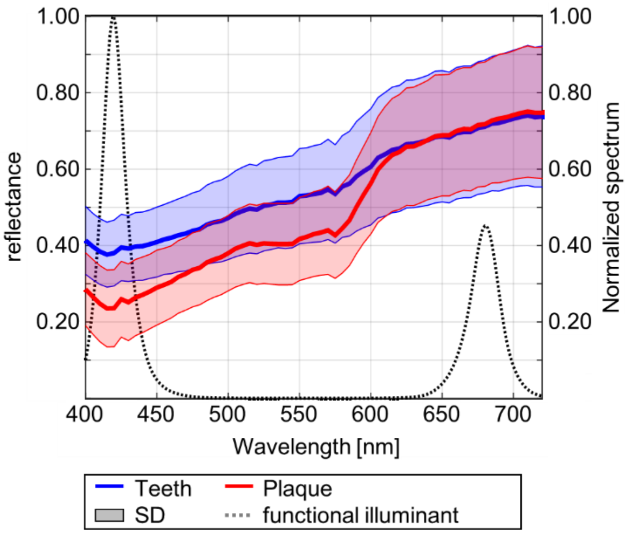


Figure 4. *Spectral reflectances of the teeth and plaque regions in the "before brushing" condition and the designed spectrum for the functional illumination (normalized)*

Table 2. Color difference between teeth and plaque for each tooth in each conditions

	Before brushing		After brushing	
	white	functional	white	functional
teeth1	12.255	33.675	11.274	30.609
teeth2	11.209	29.760	9.922	23.321
teeth3	9.817	24.629	7.216	13.319
teeth4	9.452	19.439	10.454	16.828
teeth5	10.993	26.329	13.136	28.321
teeth6	14.067	37.538	12.735	30.236
teeth7	6.111	6.593	7.797	15.071
teeth8	14.843	35.135	11.656	25.429
teeth9	10.791	29.898	5.770	16.670
teeth10	4.473	11.454	4.901	3.283
teeth11	14.810	35.605	12.844	30.943
teeth12	13.970	37.506	15.821	38.331
teeth13	16.595	35.861	15.720	31.878
average	11.491	27.956	10.711	23.403
std	3.508	10.043	3.494	9.759

this representative, the color difference defined by (4) with the white illumination is 4.473 and that with the functional illumination is 11.454. By using the functional illumination, the color difference is higher than the white illumination in the "before brushing" condition and is lower than the white illumination in the "after brushing" condition. This suggests that the functional illumination can support the visual detection of plaque on the teeth. However, the color difference was also increased by the functional illumination in the "after brushing" condition. We selected near gingiva regions as a mask extracting the color of plaque because it is known that teeth regions near gingiva have a lot of plaque. It is also known that there are tartars near gingiva of teeth. Brushing can remove plaque but it cannot remove tartars. Therefore, not only plaque but also tartar might influence the designed illumination spectrum.

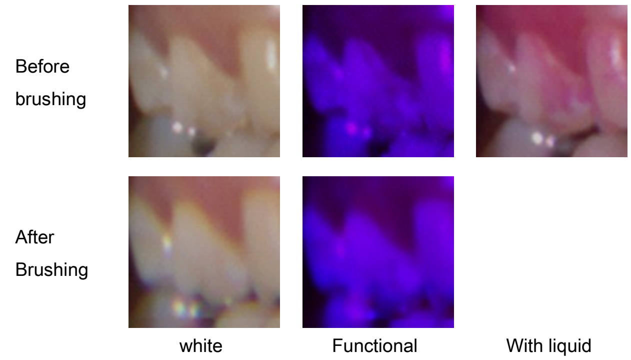


Figure 5. *Representative of the simulation (teeth10)*

Implementation

We implemented a real functional illumination by combination of LEDs that have the peak at 420 nm and 680 nm to confirm the effects for the color discrimination. Figure 6 shows RGB images of the teeth that were irradiated by the white light source and the functional illumination in the "before brushing" and "after brushing" conditions, and the RGB images of the teeth with the agent liquid. All images were taken by an RGB digital camera (EOS8000D, Canon). In the "before brushing" condition, the stained regions by the agent liquid of the teeth such as the right area of the right teeth are darker than the other regions. However, the color of the other areas in the teeth were not changed between the two conditions by each illumination. The color difference with white light source is 14.1579 and that with functional illumination is 17.106 in the "before brushing" condition. In contrast, the color difference with white light source is 10.248 and that with functional illumination is 5.707 in the "after brushing" condition. The color difference with functional illumination is higher than the white light source in the "before brushing" condition and is lower than the white light source in the "after brushing" condition. Additionally, by using the functional illumination, the color difference between the two conditions is higher than the white light source. This result shows that the functional illumination changes the color of the plaque and enhances the color discrimination between the teeth and plaque.

Next, we tested the functional illumination for other people (5 participants). The color difference between teeth and plaque of 5 participants as shown in Table 3. Fig. 7 shows RGB images of the teeth (participant 4). All images were taken by an RGB digital camera (EOS8000D, Canon). With the functional illumination, the stained regions by the agent liquid of the teeth are darker than other regions in the "before brushing" condition. However we cannot find these dark regions with functional illumination in the "after brushing" condition. The color difference with the functional illumination is higher than the white light source in the "before brushing" condition and the color difference between the two conditions is higher than the white light source. In the other participants, the functional illumination can also emphasize the color differences. The results show that the functional illumination can support the visual detection even for people different from the calibration data.

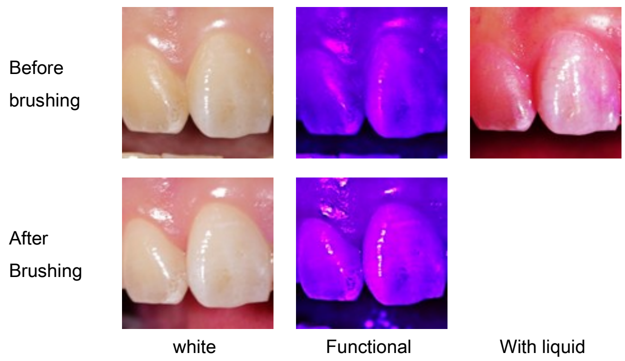


Figure 6. *RGB images of teeth taken with the white light source, the designed functional illumination and with agent liquid. The images were taken by a standard RGB digital camera (Canon EOS8000D)*

Table 3. Color difference between teeth and plaque for each tooth in each conditions

	Before brushing		After brushing	
	white	functional	white	functional
participant1	12.704	22.477	14.302	15.600
participant2	14.237	16.665	15.025	13.986
participant3	11.406	17.325	11.078	9.228
participant4	7.495	10.813	7.957	6.889
participant5	7.945	17.820	8.724	6.712
average	10.757	17.020	11.417	10.483
std	2.953	4.158	3.189	4.098

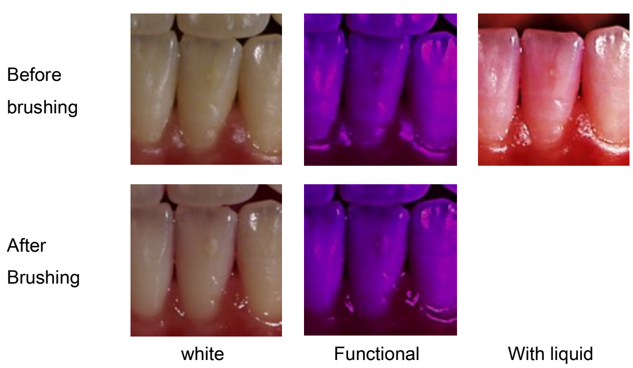


Figure 7. *RGB images of teeth taken with the white light source, the designed functional illumination and with agent liquid. The images were taken by a standard RGB digital camera (Canon EOS8000D)*

Conclusion

In this study, we propose a method for the designing of a functional illumination that supports the visual detection of the plaque on teeth. This functional illumination is implemented by LEDs and maximizes the color difference between plaque and teeth. To design the spectrum of the functional illumination, we formulate the design process as an NLP with the SQP method adopted to solve the NLP. To design the spectrum, we measured the reflectances of teeth and plaque. In order to alleviate displacements due to an observer's movement, a feature-based registration was applied to the reflectance spectrum images. The spectrum had the peak at 420 nm because the largest difference in reflectance was observed at 420 nm in the reflectance spectra between teeth and plaque. The simulation results show that the functional illumination enhances color discrimination. Additionally, the real functional illumination that was implemented with LEDs enhances the color discrimination. Moreover, the functional illumination can also enhance the color discrimination in different participants. For future works, the effects of tartars to the functional illumination design should be considered. Moreover, additional observers and evaluations with professional dentists are needed to clarify the effects of the functional illumination.

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Author Biography

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