Assessing Gloss of Tooth using Digital Imaging

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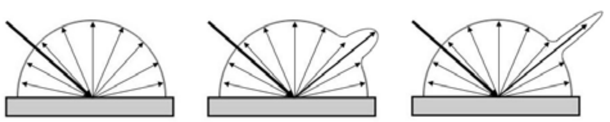
Abstract

The aim of this study was to assess gloss of tooth by digital photography. A gonio-imaging system (gonio - being Greek for angle) was developed to measure the gloss of human teeth in a laboratorial stage. Polarised and non -polarised images were acquired around the specular angle. The gloss component was extracted and normalised to a theoretical standard; a BRDF curve was built to describe the gloss profile of the subject. Porcelain teeth were used to test the repeatability of the system and several human lateral teeth were etched to check the system's capability to detect gloss changes. In addition to the BRDF, the area under the curve was calculated to give a quantitative value of gloss. The comparison result between the original and etched teeth can prove the validation of the gonio¬imaging system for measuring tooth-gloss changes.

Introduction

Gloss Measurement

Gloss is an essential property of appearance, especially for objects with smooth surface. Gloss may be defined as the "angular selectivity of reflectance, involving surface-reflected light, responsible for the degree to which reflected highlights or images of objects may be seen as superimposed on a surface" [1]. The roughness of the surface determines the angular distribution of the reflection [2]. A perfect reflecting diffuser reflects light equally at all reflecting angles, while a glossy surface reflects more light around the specular angle (opposite to the angle of the incident light). The area and the sharpness of the specular peak are important attributes of surface. Figure 1 illustrates three kinds of surfaces: perfect reflection diffuse, semi-glossy and highly glossy surfaces. Glossier surface results in sharper and narrower specular peak. The distribution of specular light is an indicator of surface roughness.



Diffuse *Semi-glossy* *Highly glossy*

Figure 1: *Light reflection on three different surfaces, a perfect diffuser, a semi-glossy surface and a highly glossy surface*

The Bidirectional Reflectance Distribution Function (BRDF) describes the directional dependence of the reflected energy. BRDF is a fundamental optical property, which characterizes the light reflected into the hemisphere above a surface as a result of incident radiation. The geometry of BRDF definition is shown in Figure 2.

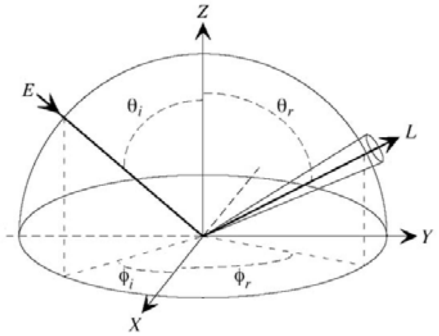
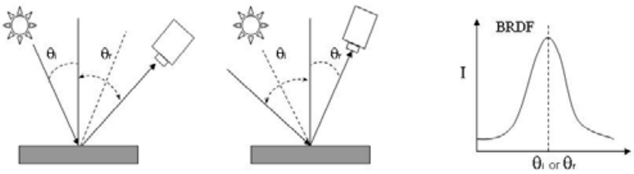


Figure 2*: BRDF geometry and angle specification. Incident direction (θ_i, φ_i) and reflected direction (θ_r, φ_r)*

From the geometry, BRDF can be defined as the ratio of the reflected light in a particular direction (θ_r, ϕ_r) to the incident light from the direction (θ_i, ϕ_i):

$$\rho(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{dL(\theta_r, \phi_r)}{dE(\theta_i, \phi_i)} \quad (1)$$

BRDF is therefore a function of four scalar variables and is too complex to be practical for many measurement instruments. Therefore, if we consider only a restricted section of the hemisphere, where ϕ_i and ϕ_r are constant (e.g. ϕ_i and ϕ_r =90^o), we can consider BRDF of incident angle θ_i and reflected angle θ_r only. The BRDF curve thus is generated and visualised in 2-dimension as shown in Figure 3 (c).



(a) *(b)* *(c)*

Figure 3*: Two types of design for goniophotometric measurement. (a) Measuring BRDF as a function of detection angle θ_r; (b) Measuring BRDF as a function of illumination angle θ_i; (c) BRDF curve.*

The angular distribution of reflected light can be measured with a goniophotometer, which is designed to measure the intensity of light reflected from a surface at various angles. Figure 3 illustrates two typical types of design for goniophotometer, either changing the detection angle or the illuminate angle. The measured reflected light is a function of the detection angle or the illuminate angle. The peak of the BRDF occurs at the specular angle. The width and the height of the BRDF curve indicate the roughness of the surface.

In accordance with Fresnell's laws, gloss increases as the specular angle increases. The angle of illumination influences the measurement result. Therefore, there is an agreement that highly glossy surfaces usually are measured at small angle, e.g. porcelain is measured at 20^o, whereas rough surfaces are measured at big angles, e.g. plain papers are measured at

75°[3].Conventional gloss meters are usually designed to be capable of measuring at an angle range from 20° to 75°.

Gloss of Teeth

Gloss plays an important role in the appearance of teeth. Recently, tooth whitening has become more popular around the world. Tooth bleaching with peroxide is one of the most common cosmetic procedures in dentistry and can be accomplished using a variety of methods [4]. As the gloss of tooth could be affected by bleaching materials [5], [6], it is necessary to consider gloss measurements alongside colour-change measurements. In dentistry, gloss is usually evaluated visually by experienced examiners who evaluate teeth according to a subjective scale. In order to get more reliable and accurate assessment, instrumental measurement is necessary. However, conventional glossmeters were designed to measure flat samples and employ light aperture sizes that are usually much bigger than the size of a human tooth. It is therefore difficult to use a gloss meter to measure tooth gloss practically.

The use of digital imaging to predict gloss has been proposed for several years [7]. Imaging-based techniques have been shown to give very good predictions of visual results [8]. For dental applications there is an interest in a non-contact measuring system. Digital imaging has the advantage of being a distant measurement, and can provide the dentist with extra information about the tooth surface such as texture and shape. Application of digital imaging in tooth gloss measurement may become an interesting and new direction in dentistry.

Experimental

Experimental Set-up

The gonio-imaging system consisted of three main parts, light source, digital camera and the subject. The basic design is illustrated in Figure 3 (b). A schematic of the system is shown in Figure 4. A 150-watt halogen cold light source (Schott KL1500 LCD) was used to provide a spot light. A focusing lens (Schott P/N 158210) was fixed on the output light guide of the KL1500 to generate a narrow beam. The light source was 28cm away from the subject to provide approximate parallel lights, and it was movable in an arc range.

As human teeth are considered to be similar to highly glossy porcelain materials, the measuring specular angle was set to be 20°. A Jai 3CCD camera was mounted at a distance of 15cm from the subject, with the angle of detection θ_r equal to 20°. This camera was chosen mainly for the capability of manual setting. The gamma of RGB channels was set close to 1.0, but a linearisation of the RGB values was applied in any case. A standard white porcelain tile was used to make sure the maximum output RGB values were less than 255 (for a camera aperture size of f4 and a shutter speed of 1/60s).

The aim of the imaging system is to generate the gloss profile of the subject. In order to extract the gloss information of an image, two polarisers were placed in front of the camera lens and the light source to exclude or include the specular light by rotation. The specular angle (20° to the normal) was notated as 0o position. In this notation, 9 positions (corresponding to -20°,-15°, -10°, -5°, 0°, 5°, 10°, 15°, 20°) were measured. Two images, polarised and non-polarised, were captured at each of the 9 positions and the difference between these two images was used as an indication of gloss.

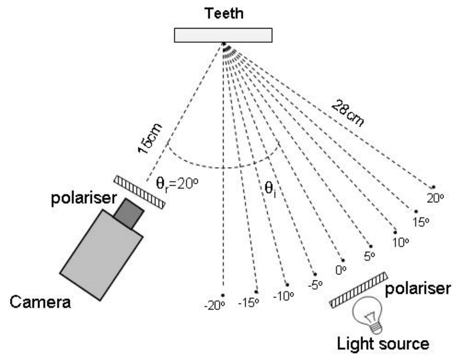


Figure 4: The experimental set-up for the digital camera to measure specular distributions of teeth.

Repeatability measurement

The stability of the light source was investigated before measuring the gloss of tooth. The intensity and colour temperature can be approximately controlled by the light source controller. In order to measure the repeatability, a tele-spectroradiometer (Minolta CS1000) was used to measure the radiance of a white tile located at the subject's position in the system. The average measured colour temperature was 2765 K. The relative SPD of the light source is shown in Figure 5.

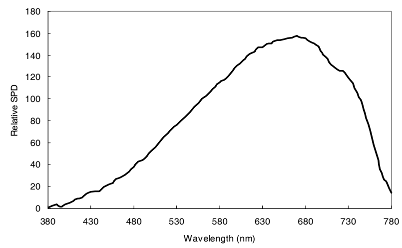


Figure 5: An average Relative SPD of the KL1500 light source in five days.

The short-term repeatability were tested by 10 measurements over 10 minutes; the standard deviation of intensity was found to be 1.9, and CV (calculated by multiplying the root-mean-square difference between pairs of points in the data sets by 100 and dividing by the mean of the data) was 1.2. For the long-term repeatability test (measured once per day for five days) the standard deviation was 4.2, and the CV was 2.8.

Since the overall repeatability of the whole system is determined not only by the light source, but also the camera and the set-up alignment, a set of porcelain teeth (Figure 6) was used as a testing subject and its gloss profile was measured over 3 days. The reason of using porcelain teeth is that their physical properties are close to those of real human tooth but they are much more stable, since properties of an extracted human tooth may change in an unprotected condition, e.g. dehydration and loss gloss in the air.

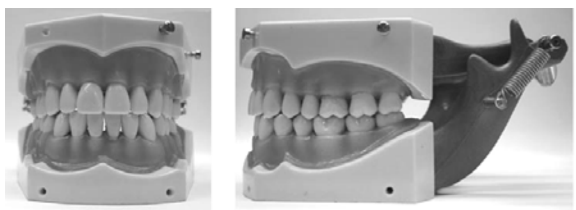


Figure 6: The porcelain teeth used in the repeatability experiment (the front view and the side view).

Teeth Etching Experiments

In order to test the system performance of measuring the gloss changes for real tooth, two experiments (I and II) of teeth etching were conducted. In the Experiment I, an extracted human molar (cheek tooth) was used as the test sample (shown in Figure 7), which was initially polished to be highly glossy to represent high gloss teeth after bleaching. After measuring the original BRDF of the tooth, a 37% phosphoric acid solution was used to etch the right side of the tooth for 20 seconds (keeping the left side untouched). The purpose of Experiment I was to compare the gloss profile of the etched and the non-etched sides of the tooth.

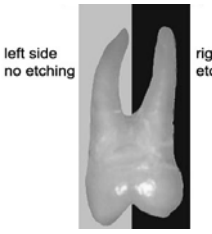


Figure 7: *The human molar in Experiment I, notated as Tooth 0.*

In Experiment II, three lateral human teeth exhibiting different levels of gloss were measured (notated as Tooth1, 2 and 3). As the teeth were natural human teeth without being polished, a milder 20% phosphoric acid was applied for 20 seconds. The BRDF of each tooth was generated and compared.

RESULTS AND DISCUSSION

System Repeatability

The gloss of the porcelain teeth was measured once a day for three days to test the overall stability of the imaging system. Polarised and non-polarised images at each of 9 positions were acquired. Some example images on the 0o position are shown in Figure 8 (a) and (b). It was known that the surface of the tooth may not be flat, which can be considered to be composed of numerous small planes that are on the directions of numerous tangents of the surface. When the detection angle is equal to the illumination angle (20^o in this experiment), the strongest specular light occurs on the plane which is perpendicular to the normal. A region of interest (ROI) was selected manually by a MATLAB GUI programme from the $_{0o}$ non-polarised image (as shown in Figure 8 (c)), and same areas were chosen automatically from images of other positions. Since the material is considered to be identical all over the tooth surface, BRDF calculated from this area can represent the gloss property of the whole surface of tooth.

(a) (b) (c)

Figure 8: *Polarised (a) and non-polarised (b) images on the 0^o position, (c) Select the region of interest (black line circle) by a MATLAB GUI on the polarised image of the 0^o position.*

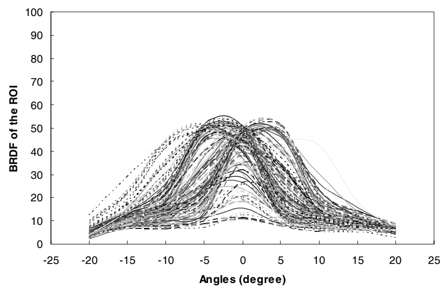
One important factor of using camera to measuring gloss is that the camera response must be linear to the input intensity. Although the camera gamma of the Jai camera was manually set close to 1.0, a further linearisation was applied to the grabbed camera RGB. A grey scale card made from a GretagMacbeth Color Checker DC was used to build the linearisation model.

The green channel value was used for measurement of gloss because it correlates well with the luminance channel of CIE XYZ space [9]. The difference of the linearised G values between the polarised and non-polarised images was calculated. General gloss measurement is made relative to a theoretical standard, which is specified to be a highly polished plane black glass with an index of refraction n=1.567 at the wavelength of 589.3 nm. In theory, this standard gives G=255 for the non-polarised image, and G=0 for the polarised image. If this glass is assigned a gloss value of 100, the measured gloss value can be calculated and normalised by Equation (2).

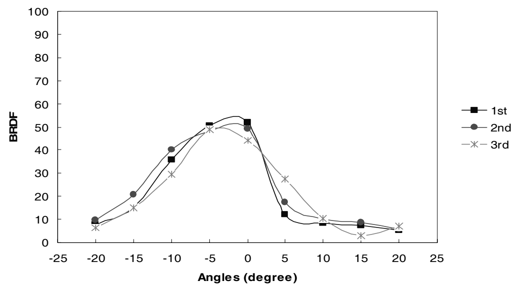
$$Gloss_i = \frac{Gn_i - Gp_i}{255} \times 100 \qquad (2)$$

where $Gloss_i$ is the gloss value of angle i, Gn_i is the green channel value of the non-polarised image on angle i, Gp_i is the green channel value of the polarised images on angle i.

The BRDF of each pixel in the ROI is shown in Figure 9 (a). It can be seen that most curves were similar in shape though some shifted along the X axis, which indicated that the surface of the ROI consists of approximated parallel planes with small angle differences. Since the physical properties were assumed to be uniform on the tooth surface, the curve with the maximum value on the 0^o direction (specular angle) was chosen to represent the gloss of tooth. The BRDF of the three-days measurement were plotted and compared in Figure 9 (b). Besides the visualisation of gloss by curves, the area under the BRDF was calculated for a quantitative result. The BRDF generated by Equation (2) is the gloss component extracted from the non-polarised image, larger area under the curve results in higher gloss. The average value of the area under the three BRDF curves was 956.4, with a CV of 4.2.



(a)



(b)

Figure 9: *(a) The BRDF of each pixel in the ROI; (b) The peak BRDF of the ROI in three days.*

Teeth Etching Results

In Tooth-Etching Experiment I, BRDF of left side and right side was calculated individually. Captured images of original and the etched tooth were shown in Figure 10, note that only the right side of the tooth was etched.

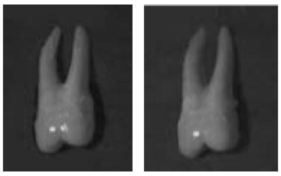
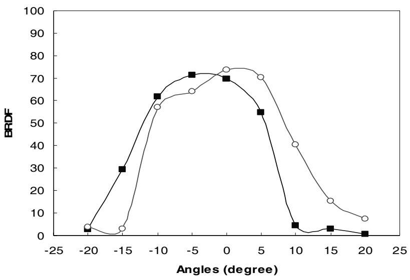
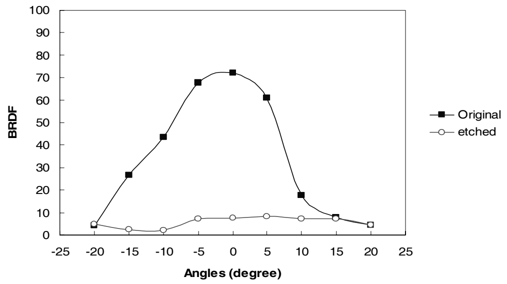


Figure 10: *Captured images of Tooth 0 (according to the teeth notation in Experiment II) before and after etching, Note that only the right was etched.*

The maximum BRDF curves before and after etching were compared (Figure 11). It can be seen that the specular light from the etched right side almost disappeared visually in the captured image (and the BRDF curve was found dramatically reduced) whereas the BRDF of the left side was almost the same in the before and after images.



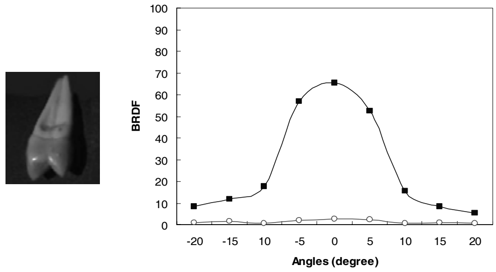
(a) BRDF of the left side



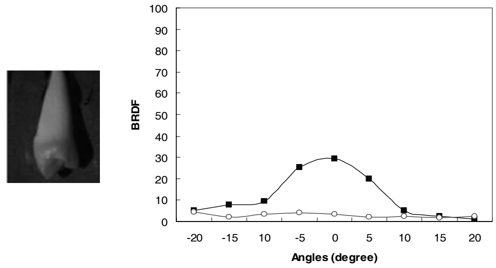
(b) BRDF of the right side

Figure 11: *BRDF of the left (non-etched) and the right side (etched) of Tooth 0.*

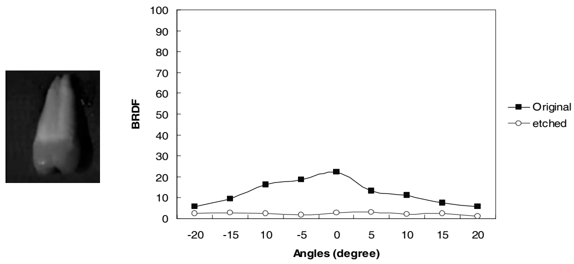
In Tooth-Etching Experiment II, three teeth with different gloss levels were etched and their BRDF were compared (Figure 12). The increase in light reflected in the 0^o direction gives an indication of the gloss of the sample. The original curve for Tooth 1 showed such a peak of reflection on the specular angle, whereas the other two teeth had much lower height of the peak. After etching, all of the three teeth had little gloss, their BRDF curves gave no evidence of a peak of reflection in the specular direction.



(a) Tooth 1



(b) Tooth 2



(c) Tooth 3

Figure 12: *BRDF of the three teeth before and after etching (Tooth 1, Tooth 2 and Tooth 3)*

Table 1 summaries the area under the BRDF curves for the four human teeth before and after etching (for Tooth 0, only the data of the etched right side is shown). From the differences between the value of the original and the etched teeth, it was evident that the gloss component decreased a large amount. Combined with the BRDF curves, the area can be a quantitative index for assessing gloss of surfaces in addition.

CONCLUSIONS

In conclusion, from the stability test and human-teeth etching experiment, the gonio-imaging system can be considered to be suitable to build the gloss profile of tooth and to be sensitive to measure the changes of gloss. These findings have implications in the use of digital camera in the assessment of gloss related to dental practices, such as tooth surface enhancement and tooth bleaching, In addition the system could be used to evaluate gloss of human teeth in a laboratorial level but the system could be modified for further measurement of patient teeth in a clinical environment.

Table 1: Area under the BRDF curves for the four human teeth before and after etching.

	Tooth 0		Tooth 1		Tooth 2		Tooth 3	
	Original	Etched	Original	Etched	Original	Etched	Original	Etched
Area	1528.9	235.3	1201.8	64.7	524.7	110.2	523.6	96.6

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Author Biography

Wen Luo completed her BSc degree (First class) in Computer Science and Communication at Southwest Jiaotong University in 2002, and then obtained her MSc degree (with Distinction) in Colour Science from the Colour Imaging Institute at the University of Derby in 2003. She is currently working on her PhD project ‘Assessment of Tooth Whiteness’ (sponsored by Colgate) under the supervision of Stephen Westland at the University of Leeds.