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Marcelo Saito Nogueira, Vanderlei Salvador Bagnato, Vitor Hugo Panhóca, "Calculation of whiteness and yellowness indexes using colorimetric and photographic methods for tooth shade evaluation," Proc. SPIE 11238, Optical Interactions with Tissue and Cells XXXI, 112381H (31 March 2020); doi: 10.1117/12.2546999

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Event: SPIE BiOS, 2020, San Francisco, California, United States

Calculation of whiteness and yellowness indexes using colorimetric and photographic methods for tooth shade evaluation

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ABSTRACT

Accurate color assessment is still a challenge for food-industrial applications and dental aesthetics. Even though current tooth color determination relies mostly on visual shade matching with shade guides, the technological advancements move towards objective tooth color assessment by using instruments such as colorimeters, spectrophotometers and digital cameras. Objective assessment of tooth color improves the communication between the professionals including clinicians, dentists, laboratory technicians and equipment designers. Tooth color can be evaluated by calculation of whiteness and yellowness indexes. Precise determination of these indexes is particularly important in dentistry, where monitoring the quality of dental restoration and the tooth appearance during whitening treatments is essential for improving the patient outcome. In this study, we evaluated the effect of tooth staining and a whitening treatment using violet illumination alone on yellowness and whiteness indexes. These indexes were quantified by colorimetry and digital photography, which were compared in terms of absolute values of the indexes and variation due to staining and whitening procedures. The violet illumination was capable of generating (36 ± 2) % of W* whiteness index recovery and (41 ± 2) % decrease on the YIE313 yellowness index. Even though the absolute W* and YIE313 values are relatively close for photographic and colorimetric methods, the indexes contrast were (37.3 ± 0.01) % and (12.8 ± 0.1) % lower for digital photography compared to colorimetry. We believe our study can be used as a guide for the evaluation of the color contrast generated on whitening monitoring devices in future studies.

Keywords: Colorimetry, tooth whitening, tooth color, digital photography, optical spectroscopy, violet illumination, light-induced whitening, visual shade matching.

1. INTRODUCTION

Accurate determination of tooth color is essential on procedures performed on aesthetic, restorative, and prosthetic dentistry. Tooth color is currently either subjectively evaluated by visual shade matching with standardized shade guides[1–10] or objectively assessed [11,12] by colorimetric [13–21], spectrophotometric[12,14,22–39], photographic[31,40–59], fluorescence[57] and other types of spectroscopic methods used to investigate biological tissues.[60–99] However, visual assessment is highly subjective on the professional's experience and factors influencing the perception of color (e.g. light intensity, direction and color balance of the light source) [100–105]. On the other hand, objective techniques allow accurate and precise color determination by any professional following the specified calibration protocol [28,33,53,106,107]. These techniques include colorimetric and photographic methods, which can provide relatively device-independent color information after converting the red-green-blue (RGB) readings to CIE La*b* or XYZ color spaces. One of the main advantages of objective color determination methods is the improvement on the communication between the professionals including clinicians, dentists, laboratory technicians and equipment designers.

Colorimetric and spectrophotometric methods provide reproducible color measurements of the target object. These methods are restricted by reading the color of a point at a time and by the error generated by curved teeth surfaces (light loss or measurement of the ambient light). Therefore, colorimetry and spectrophotometry are effective on color measurements over a relatively large and homogeneous surface. For heterogeneous surfaces, photographic techniques are

Optical Interactions with Tissue and Cells XXXI, edited by Bennett L. Ibey, Norbert Linz, Proc. of SPIE
Vol. 11238, 112381H · © 2020 SPIE · CCC code: 1605-7422/20/$21 · doi: 10.1117/12.2546999

more suitable, as the color of the surface of several teeth can be calculated from a single image. These techniques are also cost-effective approaches that can be widely implemented in the clinic. In order to translate digital photography to the clinical practice, the reliability of digital photography requires further investigation.

Previous studies reported the comparison between the visual, colorimetric, spectrophotometric and photographic methods for selection of the tooth shades. Miyajiwala et. al.[108] showed a high percentage of agreement between digital photography and spectrophotometry. Kim-Pusateri et. al[13] suggested the reliability and accuracy of spectrophotometers was higher than two digital cameras with colorimeters by evaluating the devices SpectroShade, ShadeVision, VITA Easyshade, and ShadeScan. A similar group of authors[109] reported the degree of reliability and accuracy of the digital camera with colorimeter ShadeScan is influenced by the shade guide system used to validate the shade matching. Dozic et. al.[110] compared the reliability of digital cameras ShadeScan and Ikam, the colorimeters IdentaColor II and ShadeEye, and the spectrophotometer Easyshade. The study showed the colorimeters were overall less reliable than spectrophotometers and digital cameras, the spectrophotometer was the most reliable instrument on *in vivo* and *in vitro* experiments. Even though the previous research was conducted on the reliability of the visual shade guides and devices for color determination using La*b*, XYZ, and color difference parameters, studies on the reliability of the devices for the determination of whiteness and yellowness indexes are still scarce.

In this study, we compared the yellowness and whiteness indexes of bovine teeth before staining, after staining and after whitening treatment. The indexes were calculated from colorimetric and photographic methods by using La*b and XYZ color spaces. The teeth were stained by immersion in coffee solution and treated by using violet illumination alone. This study focus on the measured whitening and yellowness indexes and respective variations after staining and whitening.

2. METHODOLOGY

2.1 Colorimeter and digital camera specifications

The colorimeter used in this study (Pocket Spec® - PocketSpec Technologies Inc. - Denver, CO - USA) works using a visible light source. The color measurement system was pre-calibrated in each experimental step by taking the color coordinate of a reflectance standard supplied by the manufacturer. This standard defines the RGB color chromaticity coordinates used for the equipment color calibration. Color readings are taken in RGB reflected intensities between 0 and 255. These measured RGB values were converted to L*a*b* and XYZ coordinates for the calculation of the whiteness and yellowness indexes.

The teeth images were taken by using the digital camera Sony Cyber-shot DSC-H50 (Sony Corporation, Minato, Tokyo, Japan). Specifications of the camera include the lens Carl Zeiss Vario-Tessar (13 elements in 8 groups, 4 aspherical, 1ED), focal length between 5.2 and 78mm (35mm focal length equivalent ranges from 31 to 465mm), zoom ratio of 15 times, aperture range from f/2.7 to 5.6 (wide mode) and from f/4.5 to 8 (tele mode), and normal focus range from 1 cm (0.4 in) to infinity. In order to not bias the RGB indexes taken from each image, we kept a nearly homogeneous illumination in the field of view comprising the area where the teeth were placed.

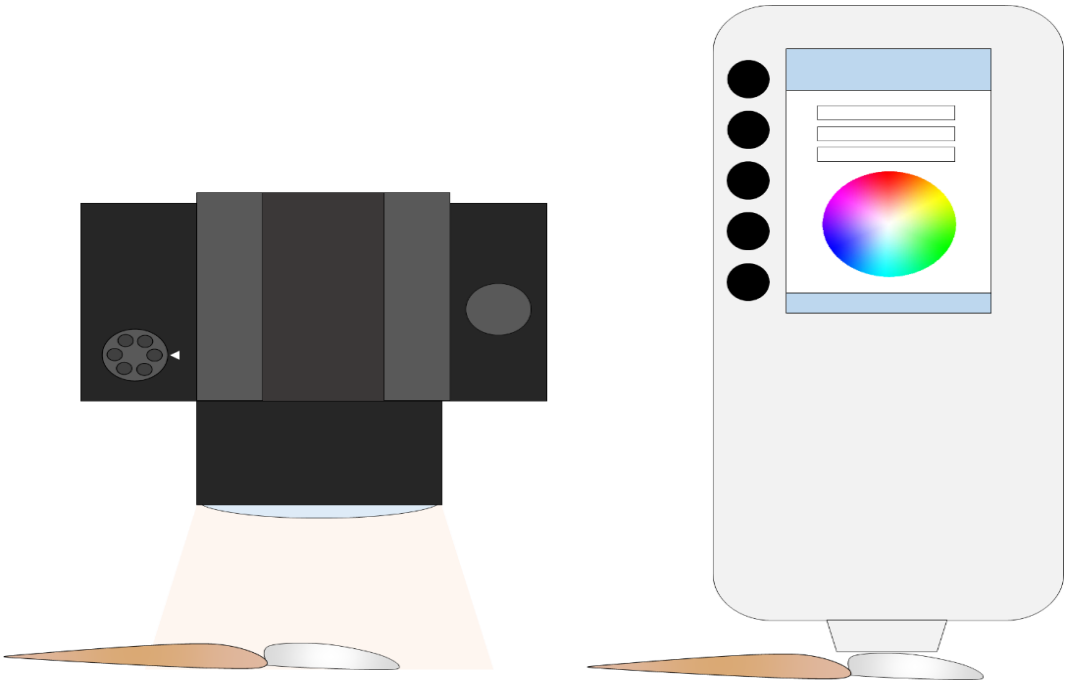

Figure 1: Schematic drawing of the use of A) photographic and B) colorimetric equipment to characterize the bovine teeth.

2.2 Sample preparation and storage

The *ex vivo* bovine teeth samples used in the study were first collected and stored in 5% thymol solution. The teeth were cleaned using curettes for periodontal scaling. The dental crown of each tooth was rinsed with water, polished with pumice stone, and scrubbed by using a Robson brush. Then, the teeth were stored at temperatures between 6 to 10 degrees Celsius until the start of the colorimetric and photographic measurements. Teeth going through the staining process were immersed in 10 mg/ml coffee solution. The teeth were kept in the coffee solution for 24 hours. After staining, teeth were submitted to a whitening treatment by shining violet light (408 ± 10 nm) at estimated power of 1400 mW for 20 cycles, which comprising 1 minute of illumination and 30 seconds of pause. More details are described elsewhere.[65,93]

2.3 Data processing and analysis

The colorimetric and imaging data was analyzed in the Microsoft Excel (Microsoft Corporation, Redmond, Washington) and MATLAB (Natick, Massachusetts, United States) software. Both data were plotted using the Origin software (OriginLab Corporation, Northampton, Massachusetts, USA).

The collected RGB data was converted to the L*a*b* and XYZ color spaces in order to calculate the whiteness and yellowness indexes. The whiteness index used in this study is calculated using the equation:

$$W^* = 100 - \sqrt{\left(\left(100 - L^{*2}\right) + a^{*2} + b^{*2}\right)} \qquad (1)$$

and is based on the distance between the L*a*b* color space coordinates to a nominal white point (L=100, a*=0, and b*=0) and the coordinates of the measured points.[50] The yellowness index YIE313[111] was calculated by using the equation:

$$\text{YIE313} = \frac{100}{\text{Y}}(1.3013\text{X} - 1.1498\text{Z}) \qquad (2)$$

In order to compare the whiteness and yellowness indexes between the photography and colorimeter, we took the measurement average and standard deviation of 5 points for the colorimeter and the points on each tooth surface in the

image. The variation on a given index $\Delta I_{procedure}$ after modification steps (control to stained teeth, control to whitened teeth or stained to whitened teeth) was calculated by using the equations:

$$\Delta W^*_{after\ staining} = W^*_{after\ staining} - W^*_{control} \quad (3)$$

$$\Delta W^*_{after\ whitening} = W^*_{after\ whitening} - W^*_{control} \quad (4)$$

$$\Delta W^*_{before\ and\ after\ whitening} = (W^*_{after\ whitening} - W^*_{after\ staining}) \quad (5)$$

Finally, the difference between the indexes of photographic or colorimetric methods calculated

$$\Delta W^*_{photography-colorimetry} = W^*_{photography} - W^*_{colorimetry} \quad (6)$$

3. RESULTS AND DISCUSSION

3.1 Whiteness index quantification

Figure 2 shows the whiteness index measured by using the digital camera and image processing had a similar tendency compared to the index measured with the colorimeter. The error bars suggest that significant differences compared to the control group can be observed in both whiteness quantification methods. In addition, the uncertainty in the whiteness index was observed to be higher when measured with the colorimeter. The larger error on the colorimeter may be associated to the measurement of fewer points on the teeth surface, which may not be representative of the whole tooth surface in case of high heterogeneity or roughness.

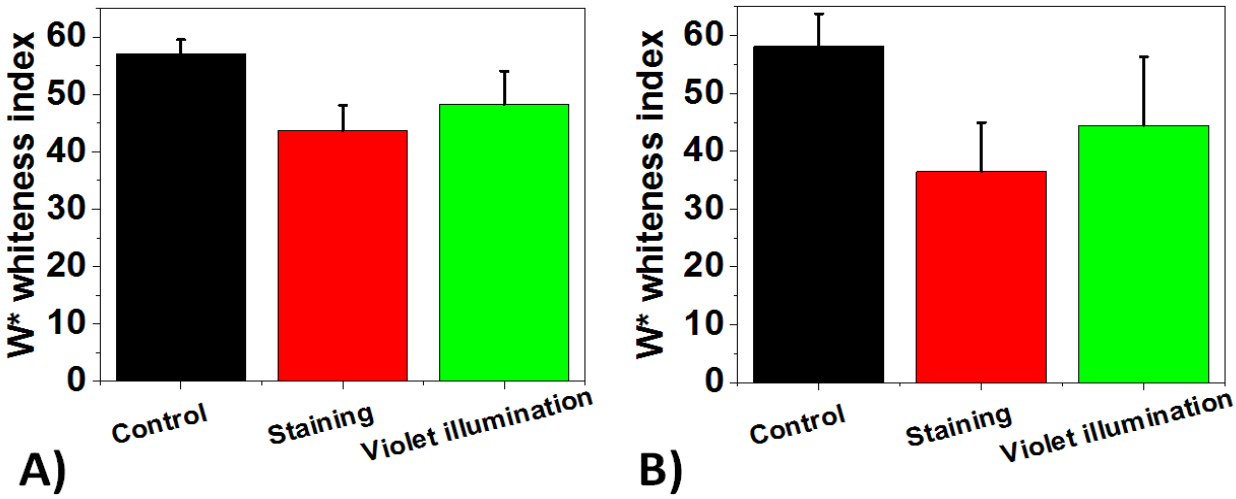

Figure 2: Whiteness index W* calculated for the control group, stained group, and violet illumination group by using A) the photographic method and B) the colorimetric method.

The effect of the violet illumination treatment was able to increase 4.59 units (figure 2A, 8% of the control whiteness index or 34.4% whiteness recovery, i.e., 34.4% of the difference between the stained and control groups) on the whiteness index scale for the photographic method and 7.25 units (figure 2B, 13.8% of the control whiteness index or 36.7% whiteness recovery) for the colorimetric method, respectively. Mori et. al.[112] reported the whitening effect of tooth bleaching with 35% hydrogen peroxide on coffee stained tooth. The whitening index the authors used was the same as the

W* calculated in this study. The authors' results suggested the W* was 38.04 ± 1.51 for coffee stained teeth on the day of the staining. This value is closer to the W* value we obtained for the colorimeter in the present study (36.4561 ± 8.49441). This closeness may be an evidence the colorimeter measurements are more reliable in terms of determination of absolute W* values. The same study reports a difference of 8.93 ± 1.26 on the whiteness index right after the tooth bleaching, which is higher than obtained in this study (4.59 for the photographic method and 7.25 for the colorimetric method). On the other hand, tooth bleaching using hydrogen peroxide, carbamide peroxide, and sodium perborate[113] may cause changes to tooth surface roughness[114–118], composition of the organic matrix [119–122], and demineralization.[115,123–125]

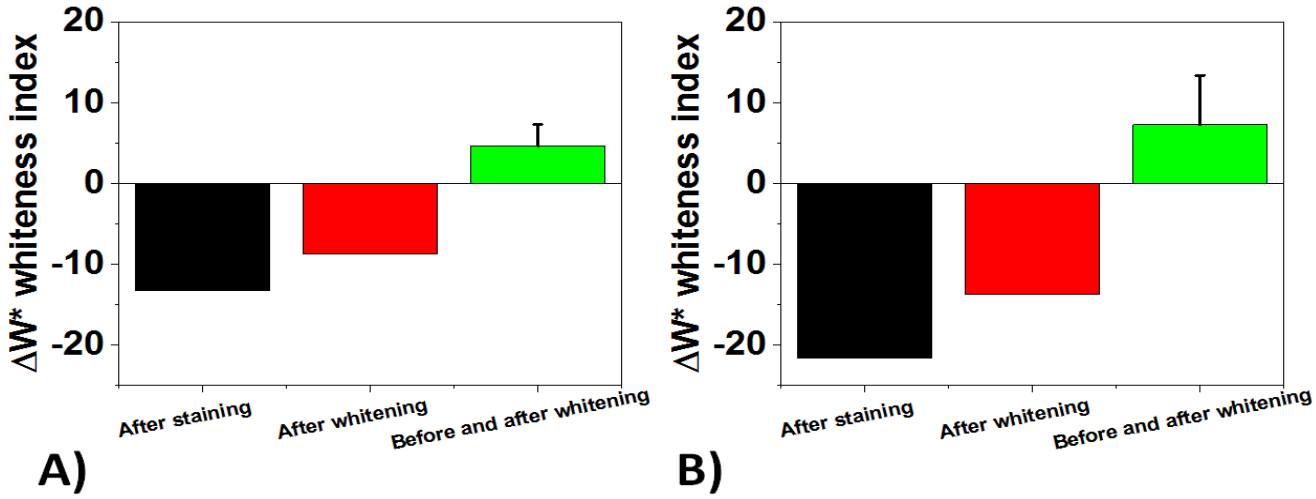

Figure 3: Variation of the whitening index W* between the control and stained teeth, between control and teeth after the whitening treatment, and between before and after the whitening treatment by using A) the photographic method and B) the colorimetric method.

Figure 3 indicates the variation (or contrast) on the whitening index W* was (37.3 ± 0.01) % lower for digital photography compared to colorimetry. Thus, even though the absolute values of the whiteness indexes are comparable, the W* contrast between stained and non-stained teeth may differ significantly between photographic and colorimetric methods.

3.2 Yellowness index quantification

Similarly to the determination of whiteness indexes, figure 4 suggests the yellowness index measured by using the digital camera and image processing exhibited similar trends compared to the index measured with the colorimeter.

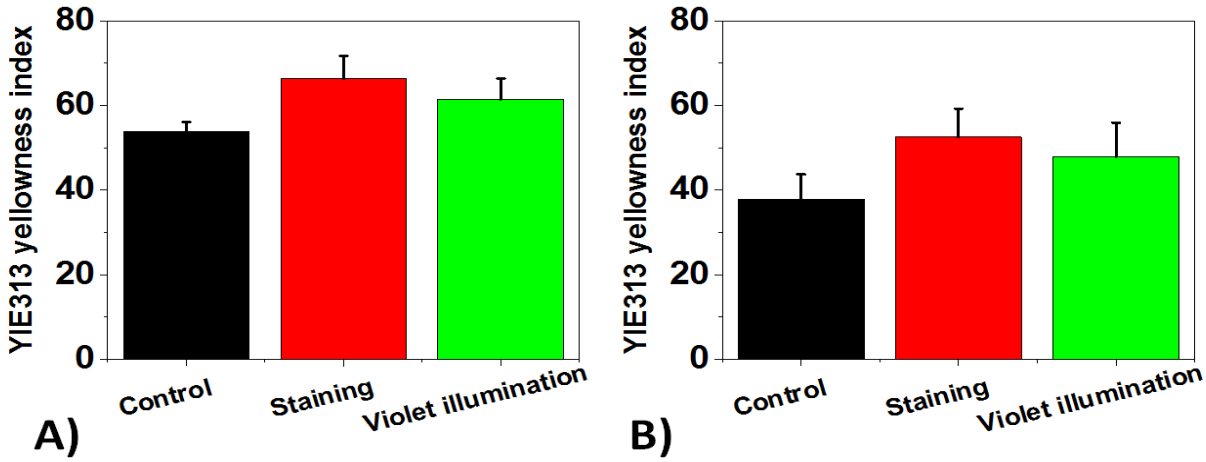

Figure 4: Yellowness index YIE313 calculated for the control group, stained group, and violet illumination group by using A) the photographic method and B) the colorimetric method.

The yellowness index decreased 4.9 units for digital photography (9% of the yellowness of the control group and 39.1% of yellowness removal, i.e., 39.1% of the difference between the stained and control groups) and 6.3 units for colorimetry (16.6% of the yellowness of the control group and 42.5% of yellowness removal), respectively. The variations can be observed in figure 5, which shows the variation (or contrast) on the photographic yellowness index YIE313 was (12.8 ± 0.1) % lower than the colorimetric index. This indicates the YIE313 contrast varies relatively less between photometric and colorimetric methods.

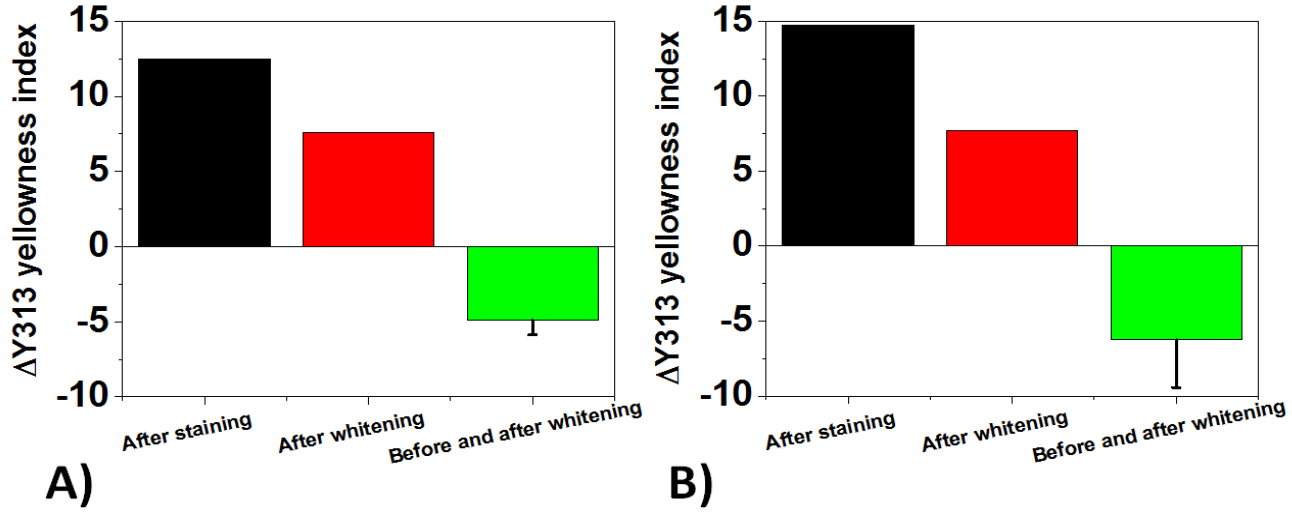

Figure 5: Variation of the yellowness index YIE313 between the control and stained teeth, between control and teeth after the whitening treatment, and between before and after the whitening treatment by using A) the photographic method and B) the colorimetric method.

3.3 Differences between photographic and colorimetric methods

Figure 6 shows the W* difference between photographic and colorimetric methods is not consistent over the control, stained and whitened groups. The whitening index may be more sensitive to the tooth surface heterogeneity, as the colorimeter measurements are based on five different positions instead of taking into account the whiteness index of every position on the tooth surface. On the other hand, the YIE313 difference was uniform over the teeth groups and may be considered a more reliable parameter when comparing results between digital photography and colorimetry.

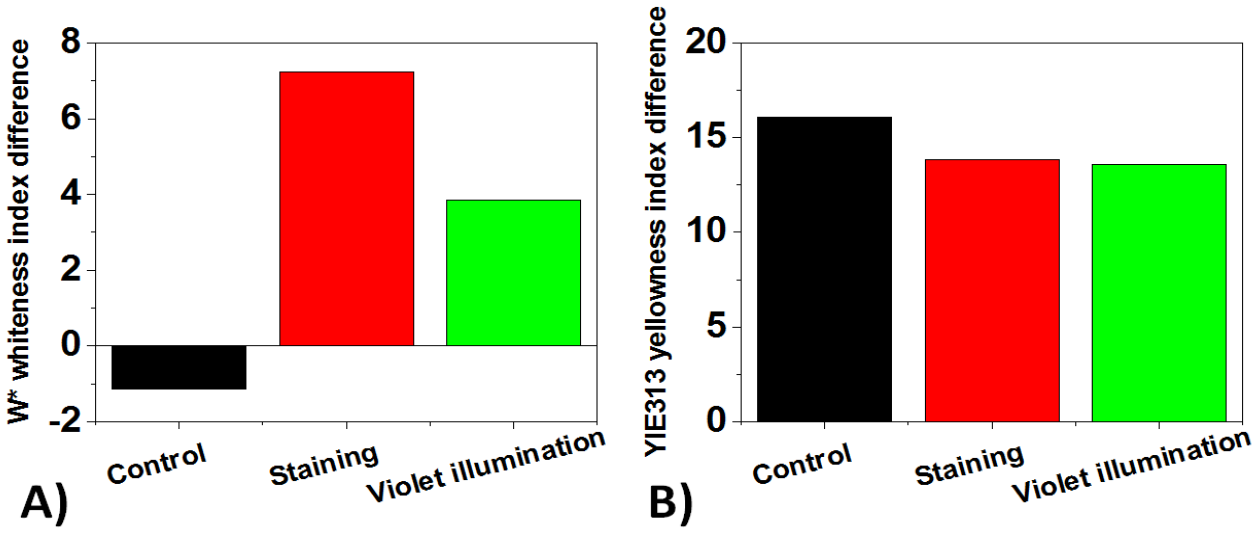

Figure 6: Difference between the photographic method and the colorimetric method on the quantification of the A) whiteness index W* and B) yellowness index YIE313.

Except by the W* of the control group, the W* and YIE313 values were higher for photometric methods compared to colorimetric methods. Particularly for the YIE313 yellowness index, the difference was (27.8 ± 0.6) % higher for digital photography. Previous studies[13,108–110] have compared the reliability, accuracy and color difference determined by spectrophotometry, colorimetry, digital photography, and visual inspection. The calculations of the compared parameters was performed through the comparison with shade guides and absolute values of CIELa*b* or XYZ color components. However, these studies do not assess the whiteness and yellowness index nor the color contrast between stained and sound teeth. Our study can be used as a guide for the evaluation of the color contrast generated on whitening monitoring devices in future studies. In addition, we compared the effect of the color contrast after the whitening treatment modality using violet illumination alone.

4. CONCLUSIONS

In this study, we evaluated the effect of tooth staining and a whitening treatment using violet illumination alone on yellowness and whiteness indexes. These indexes were quantified by colorimetry and digital photography, which were compared in terms of absolute values of the indexes and variation due to staining and whitening procedures. The violet illumination was capable of generating (36 ± 2) % of W* whiteness index recovery and (41 ± 2) % decrease on the YIE313 yellowness index. Even though the absolute W* and YIE313 values are relatively close for photographic and colorimetric methods, the indexes contrast were (37.3 ± 0.01) % and (12.8 ± 0.1) % lower for digital photography compared to colorimetry. Differences between photographic and colorimetric methods were only consistent for YIE313 ((27.8 ± 0.6)% higher for digital photography). We believe our study can be used as a guide for the evaluation of the color contrast generated on whitening monitoring devices in future studies. Further investigation is still necessary for other types of whitening treatments and between tooth shade monitoring instruments.

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