# Dental Color Reproduction System with AI Object Recognition Technology

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## Abstract
***This study proposes a dental color reproduction system that captures and calibrates images, achieving an average color difference of less than 3. This enhances color matching accuracy in prosthetic fabrication, reduces rejection rates, and improves communication between dentists and patients.***

## Keywords
Color Reproduction; AI Object Recognition; AI Object Segmentation; Dental Shade Matching.

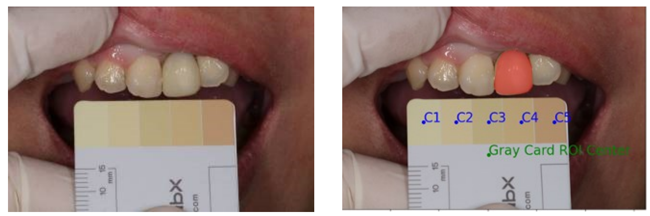
## 1. Introduction
Denture fabrication is a long-established technique that relies heavily on professional experience. Recent advancements in technology and the integration of digital tools have significantly improved the efficiency of the entire process, including data recording, image transmission, and denture mold creation. However, achieving accurate tooth color, which is a crucial aspect of denture fabrication, is often challenging and cannot be done in a single step. It typically requires multiple revisions and resubmissions, along with continuous communication and adjustments among the patient, dentist, and dental technician to align with expectations and ultimately restore the patients' confident smiles.

Listening to feedback from the field revealed that the key to determining the color in denture fabrication lies in recording images of the patient's teeth. Dentists or dental assistants often capture images using commercial cameras or smartphones to document the features of the teeth, such as surface texture, color, and distribution of translucency. Observing the workflow and listening to feedback revealed that the images captured and displayed often do not undergo accurate and stable cross-media color reproduction. This includes the calibration of the camera, the correspondence with the display monitor, and the control of lighting. As a result, the colors seen by the dental technician are distorted, making it impossible to create colors based solely on the observed images.

Instead, repeated adjustments must be made using third-party references such as shade guides, colorimeters, or color-matching software. This makes the communication and fabrication processes between the clinician and the patient cumbersome and less intuitive. Although there has been some improvement in rejection rates, issues continue to occur.

## 2. Method
The method proposed in this paper is based on the cross-media reproduction process and focuses on optimizing and adjusting the imaging and display of teeth by taking into account usage scenarios and ambient lighting conditions. Consequently, the images of the teeth are processed through four key stages: AI object recognition and segmentation, camera color conversion and calibration, adaptation to ambient light, and display reproduction. This aims to meet the needs of the dental field and bring it closer to the ideal of comparative color matching procedures.

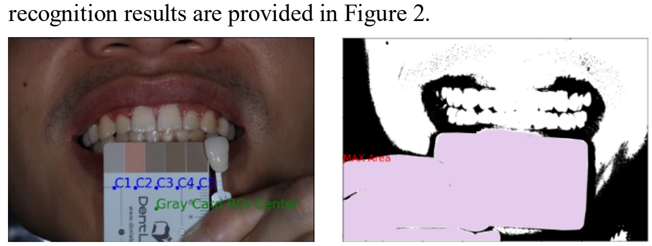
### 2.1. AI Object Recognition and Segmentation
In the dental shade matching system, object recognition is employed to extract two crucial pieces of information: the calibration color reference and the target teeth. The calibration color reference serves as the necessary image reference for the ambient adaptation process, and it includes important information such as gray colors and five shades of interest. The target teeth represent the focus of the display reproduction process, which is used to produce shade matching results. Therefore, it is essential to extract the dental region from the images for subsequent calculations and conversions. An illustration of the extraction of actual shade matching image data is shown in Figure 1.




(a) Shade matching image (b) Data extraction

**Figure 1.** Shade matching image data extraction

The object recognition and segmentation established using techniques such as image preprocessing, contour detection, and color brightness threshold control cannot adequately address the variability in captured results in different field conditions. Factors such as shooting distance, camera settings (ISO, aperture, shutter speed, etc.), and flash can affect the color and brightness of the images, rendering brightness threshold control ineffective. Additionally, the image content, the positioning and angle of the calibration color reference, and the shape of the teeth can also affect contour detection accuracy. Examples of incorrect object recognition results are provided in Figure 2.



(a) Camera settings (b) Image content

**Figure 2.** Incorrect object recognition results

To address the diverse usage scenarios in the field, this study develops object recognition and segmentation capabilities through AI model training. A variety of shade matching images were collected, encompassing different cameras such as Canon and Nikon, various camera settings including ISO, aperture, and distance, as well as different placements of calibration color references (e.g., above, below, tilted). Additionally, various content objects, such as shade guides, gloves, and mouth openers,


ISSN 0097-996X/25/5601-0477-$1.00 © 2025

were included, resulting in a total of 800 images. Of these, 700 images were designated for model training, while 100 images were used for validation. Furthermore, a practical field test was conducted with 3,800 images, achieving a 100% success rate in recognition and segmentation. The illustrations of the training images are shown in Table 1.

**Table 1.** Training image

| | | |
|---|---|---|
| 1 | Camera & settings |  |
| 2 | Different placements |  |
| 3 | Image content |  |

## 2.2. Camera Color Conversion and Calibration

The imaging device captured images in RGB format, requiring reference to the camera settings for color specifications (color gamut and white balance) to perform color conversion. The RGB data was processed into color representations such as XYZ and Lab. However, the conversion results typically exhibited discrepancies compared to actual colors, necessitating camera color calibration.

The color calibration swatch set in this paper included not only the commonly used Macbeth 24-color chart but also referenced Lab color space designs for tooth shades used in denture fabrication [1][2]. The color data obtained from capturing, converting, and measuring the calibration swatches were introduced into various models for training. Calibration parameters for the camera were deemed complete when the average color difference of the swatches was less than 3 and the model demonstrated effective generalization. These calibration parameters were applicable only to the same camera equipment and settings. Any changes in the camera equipment or settings, such as aperture, shutter speed, ISO, or white balance, required the recalibration of parameters. The detailed process for camera color conversion and calibration is illustrated in Figure 3.

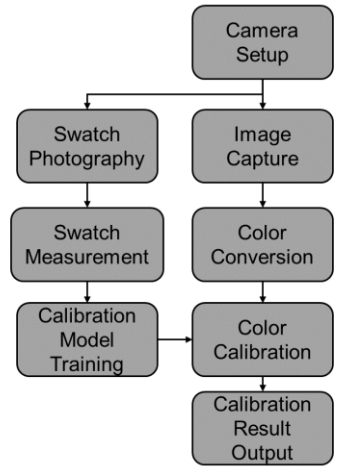



**Figure 3.** Camera conversion and calibration process

## 2.3. Adaptation to Ambient light

The image data processed through camera conversion and calibration exhibited accurate colors without distortion; however, it could not be directly used as the final output. This is because the fabrication of dentures is performed under a specific light source for color matching, which often differs from the imaging light source. Therefore, it is essential to consider the impact of light source discrepancies on the object's color and to establish corresponding parameters to compensate for the color variations in the images.

This paper uses the color data extracted from the calibration color reference identified through AI as a starting point. Based on the color temperature and brightness of the ambient light, target values for the calibration color reference are established. With these two data sets to establish the corresponding parameters for ambient light, as shown in Equation 1. These parameters are then applied to complete the color brightness compensation for the differences between the imaging light source and the color matching light source.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{Colors}_{Ambient\ light} = \begin{bmatrix} M_1 & M_2 & M_3 \\ M_4 & M_5 & M_6 \\ M_7 & M_8 & M_9 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{Colors}_{Photo\ light} \quad (1)$$

## 2.4. Display Reproduction

The optical data of the display, such as brightness, chromaticity, and gamma, were measured. The image data, which underwent color calibration and compensation for ambient light, were then converted to display RGB for accurate reproduction.

In addition to realistically rendering tooth images for dental technicians to conduct actual denture color matching, quantitative color results for the target teeth, such as Lab values, were also provided. This allows dental technicians to also perform digital color matching for denture fabrication. An illustration of the color matching scenario is shown in Figure 4.

(a) Physical (b) Digital

**Figure 4.** Color Matching Scenario for Display Reproduction

**Table 2.** Perception of color difference[4]

| Level | DEmin | DEmax | Perception of color difference |
|---|---|---|---|
| 1 | 0.0 | 1.5 | Hardly |
| 2 | 1.5 | 3.0 | Noticeable |
| 3 | 3.0 | 6.0 | Appreciable |
| 4 | 6.0 | 12.0 | Obvious |
| 5 | 12.0 | ∞ | Very Obvious |

## 3. Results

The method proposed in this study establishes a dental color matching system utilizing the AUO A.R.T. monitor in conjunction with a color matching light source. The A.R.T. monitor is equipped with exclusive advanced reflectionless technology (A.R.T.), which effectively reduces interference from ambient light and features a high Ambient Contrast Ratio (ACR). Experiments have confirmed that under bright light sources, the A.R.T. monitor achieves an ACR approximately 18 times higher than that of typical monitors used in dental settings [3]. The colors and clarity of the screen are largely free from distortion, allowing both dentists and dental technicians to observe the representations of tooth color, reflective gloss, and three-dimensionality, as illustrated in Figure 5. The specifications for the color matching light source were based on field recommendations, with a Color Rendering Index (CRI) exceeding 95 and a color temperature range of 5500K to 6500K.

(a) Standard Monitor (b) A.R.T. Monitor

**Figure 5.** Effect of Ambient Light on the Monitor

The experiment validated four cameras: Canon 6D, Canon R, Canon RP, and Nikon D7500. After calibration, the average color differences for each camera were 1.78, 1.77, 2.02, and 2.18, all of which were below the threshold of 3. The data corresponds to a reference table for human vision perception, where the perceived level of color difference is considered noticeable (refer to Table 2). The results demonstrate that this color matching system exhibits high accuracy and reliability in both physical and digital color matching. The perceived level of color difference was based on a standard technical document [4].

## 4. Conclusion

The dental color reproduction system proposed in this study is effective and accurate for tooth color display reproduction, with an average color difference of less than 3. It not only shows realistic tooth images but also provides users with precise quantitative data on tooth color, allowing the system to incorporate both digital and physical color matching functionalities. In the future, efforts will continue to enhance the reproducibility, stability, and compatibility of the color matching system.

## 5. Impact

The dental color reproduction system not only displays realistic tooth images but also provides users with precise quantitative data on tooth color, allowing the system to incorporate both digital and physical color matching functionalities. This enhances the process of communication between dentists and patients while also improving the accuracy of tooth color matching data and reducing the rate of returns.

## 6. Acknowledgements

This research paper would like to express gratitude to Chien-Mei Medical Investigation Co., Ltd., DentLabX Co., Ltd., and AUO Display Plus Corporation for their technical support and domain knowledge, which greatly assisted in the establishment of the reproduction system and its field verification. Additionally, their assistance in collecting user feedback has been instrumental in improving the deficiencies and inconveniences of the colorimetric system.

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