Title: Optical Properties and Color Stability of Denture Teeth – A Systematic Review

Running title: OPTICAL PROPERTIES OF DENTURE TEETH

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Abstract

Purpose: To systematically review past studies to determine the effect of various solutions on the color of denture teeth, thus answering the question in regards to which type of denture teeth has the best optical properties after exposure to various solutions. The method of measuring the color of artificial teeth was also evaluated as a secondary outcome.

Materials and Methods: A search of studies that quantitatively investigated the influence of immersion solutions on the color change of denture teeth was conducted. Ovid MEDLINE, PubMed and Scopus databases were searched from 1997 to April 2021. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used during article selection. Data regarding the effect of immersion solutions, accelerated aging and surface treatments on color change were gathered. Methodologies used to assess optical properties were also summarised and compared. The modified CONSORT checklist was used to determine the risk of bias of past studied included in this review.

Results: 133 studies were identified after removing duplicates. Forty-one studies were selected for full-text analysis, and 35 remaining papers met the inclusion criteria and were therefore included in this systematic review. Thirty-two in vitro studies and 3 in vivo studies were included in the review. All studies reported that immersion in various solutions has a significant influence on the change in color and optical properties of denture teeth. However, the discolouration of denture teeth is still clinically acceptable in most studies. Exposure to various solution also affected the translucency parameter of denture teeth. Most studies also investigated the surface roughness and hardness along with the optical properties, and reported that immersion cycles did not cause changes in surface roughness of denture teeth, while hardness was affected. The optical properties of PMMA denture teeth have been studied extensively, whereas that of CAD/CAM and 3D printed denture teeth is limited.

Conclusions: Color stability of CAD/CAM milled denture teeth is comparable to conventional PMMA denture teeth. There are contradictory findings in terms of color stability of 3D printed denture teeth as compared to conventional PMMA denture teeth. Staining by coffee is worst among the common beverages and solutions investigated. Denture teeth can show color changes after immersion in staining beverages as early as one week. The degree of discoloration of denture teeth after immersion is time dependent, with the larger extent in the initial phase.

Keyword: Optical properties; denture teeth; color stability; color change; systematic review

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The color stability of denture teeth is one of the most important and clinically relevant optical properties of dental materials since color change indicates aging or deterioration of material.[1] Stain accumulation, water sorption, degradation of intrinsic pigments and increasing surface roughness contribute to color change.[2] The color changes affect the overall esthetics of a prosthesis, affecting patient satisfaction of a removable prosthesis and long-term quality of life.[1,3]

Color evaluation of dental materials, like denture teeth can be done via visual and instrumental methods.[4] A frequently used instrument is a spectrophotometer which measures spectral transmittance and spectral reflectance of objects. Color differences can be calculated using various formulae as outlined by the International Commission on Illumination (CIE), with CIE 76 (denoted ΔE^*_{ab}) and CIEDE2000 (denoted ΔE_{00}) being the two common formulae used. Besides mere calculation of the color difference between two objects, interpretation of color differences is important as it gives clinical relevance and practical implication to the reader. It is often done through 50:50% perceptibility and acceptability visual thresholds and sometimes the National Bureau of Standards (NBS) ratings.[5] On top of color, translucency affects the natural appearance of artificial teeth and translucency similar to natural teeth is an important characteristic for better esthetics.

Restorative materials used in dentistry are exposed to various coloring agents, including certain food or beverages and oral hygiene products, contributing to the pigmentation of the resin matrix.[1, 6] Therefore, color stability of various types of denture teeth after immersion in different beverages and solutions has been investigated extensively.[2, 7-11] Beverages such as coffee, red wine, tea and various disinfecting solutions were used. The use of different materials and methods led to great heterogeneity in published results. Differing immersion times, ranging from days to weeks to months

and differing artificial aging protocols with varied cycles of simulated immersion were also adopted across studies.[9, 12-15]

With the advancement of digital technology in the recent years, computer-aided design and computer-assisted manufacturing (CAD/CAM) and 3D printing have been widely applied in dentistry.[2, 16, 17] The application of these new technologies has become increasingly popular in removable prosthodontics such as complete and partial dentures to treat patients missing some or all of their teeth.[18] With the CAD/CAM technology, denture teeth are milled from pre-polymerised acrylic resin blocks that were formed under intense heat and pressure. 3D printing, also known as additive manufacturing, fabricates denture teeth layer by layer in a printer, and the layers are usually polymerised by an ultraviolet light source intermittently.[16] Despite their time and cost saving technology, the monolithic and dull aesthetic of the CAD/CAM and 3D printed denture teeth has been criticised.[16] However, there is lack of studies providing information on the optical properties of these materials, and whether it is comparable to the conventional Polymethylmethacrylate (PMMA) denture teeth.

To the best of the author's knowledge, there is no published attempt made on summarising and systematically analysing the large body of literature available on this topic. Therefore, a comprehensive evaluation of the available data can be beneficial to identify the type of denture teeth with best optical properties. In addition, the present work intends to overview the method used for color measurement to give guidance to the most suitable methodology to investigate the color changes of the modern denture teeth.

Materials and Methods

Search strategy

The systematic review was developed according to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement. The Patient or Population, Intervention, Control or comparison, Outcome and Study types (PICO) model was used to define the evaluation criteria (Table 1). The overall search strategy and search keywords are presented in Table 2. Database searches were limited to the English language and studies published between 1997 and 2021.

Study selection

Two independent reviewers (M.T. and J.C.) initially reviewed the titles and abstracts of all the collected articles. After application of the inclusion and exclusion criteria, full-text articles were obtained and further evaluated. All differences in choices between the two authors were analysed and an agreement was established through discussion as per Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Fig. 1).[19] In addition, bibliographies of selected articles were subjected to detailed search for potentially relevant articles. A further manual search was done to supplement the electronic search.

Data extraction and method of analysis

The two reviewers independently extracted the data from all included papers and registered on a spreadsheet in Excel format (Microsoft Corporation, Redmond, WA, USA). The information extracted from the selected articles for analysis were author(s), years of publication, type of denture teeth investigated, immersion solutions used, immersion period and aging protocol adopted,

equipment for color measurement, evaluation methods of optical properties, and any further qualitative analysis.

Assessment of risk of bias

The modified Consolidated Standards of Reporting Trials (CONSORT) checklist was used to evaluate the methodological quality of each study included in this systematic review.[20] Articles reporting one or two items encoded as yes were classified as high risk of bias, three items as a medium risk of bias and four items as a low risk of bias.

Results

Search and selection

After screening of databases and removing duplicates, 133 articles were identified (Fig 1). Only 39 articles remained after title screening. Articles were further excluded after careful examination of the abstracts. The full texts of those 39 studies were assessed and only 31 articles met the inclusion criteria. After merging with hand searched articles, 35 articles were included in the review.

Risk of bias

The modified CONSORT checklist was used to evaluate the methodological quality of the included studies, presented in Table 3.[20] All included studies provided adequate details on measurement of color. Although different immersion solutions were used, they were clearly described. All studies provided adequate report on abstract, background and objectives, intervention and outcomes. Only 3 studies reported on how sample size was determined. Items related to randomization, allocation, implementation, and full trial protocol access were not clearly

reported in any of the included studies.[9, 13, 17] Only 1 study reported on blinding.[2] Statistical methods and results were not reported in 3 studies.[7, 10, 21] Limitations and fundings were not always adequately reported. None of the studies reported on the availability of full trial protocol. Risk of bias for all studies is presented in Table 3.

Main findings

Conventional PMMA-based denture teeth were extensively studied and included in all studies, while double cross-linked (DCL) PMMA denture teeth were included in 16 studies.[2, 9, 11-14, 22-31] Nanocomposite denture teeth were investigated in 4 papers,[21, 23, 26, 32] while 1 study[33] looked at composite resin teeth. Porcelain teeth were studied in 4 papers.[11, 31, 34, 35] CAD/CAM and 3D printed denture teeth materials have gained popularity recently and were investigated in 3 studies out of 5 published in 2020.[2, 16, 17] Al-Qarni et al[2] reported on CAD/CAM materials while Koh et al[16] reported on 3D printed material. Gruber et al[17] looked at both CAD/CAM and 3D printed material. Before 2020, only two studies investigated CAD/CAM-fabricated polymers, which were by Cristache et al[21] and Güth et al.[36] Comparisons were made between denture teeth manufactured via those methods against conventional heat-cured denture teeth.

Among the in vitro studies, different immersion solutions, immersion period and ageing protocols were adopted, which prevented a meta-analysis to be conducted (Table 6). Of these, two studies reported the effects of acidic beverages,[12,13] ten studies reported the effects of denture cleaners or disinfectants.[14, 22, 25, 26, 28, 34, 37-40] Distilled water was most often used as a control, whereas artificial saliva was used instead in only four studies.[12-14,27] Six studies adopted an artificial aging protocol with varied cycles of simulated aging, while the remaining studies only conducted immersion over a period of time. The period of immersion varied between studies (Table 6), with 7

and 14 or 15 days being the most popular timeframes. Among the 3 in vivo studies included, different durations of clinical use were investigated, such as 6 to 18 months,[41] one year,[21] and five years.[24]

Many methods can be used to assess tooth color, including visual subjective comparisons such as using an acrylic resin shade guide and instrumental objective measurements using spectrophotometers.[6] The most common method for color measurement across all studies is via a spectrophotometer, with the most common device used being Vita Easy Shade, as seen in 12 out of 34 studies.[2, 10, 12, 14, 21, 23, 24, 26, 29, 37, 38, 42] A spectrophotometer provides more information for color evaluation than a dental shade guide, as numerical value of various color coordinates are given. However, the method of using a dental shade guide is still arguably useful as this is how color changes are most frequently measured clinically, as seen in the study done by Roslan et al.[7]

The International Commission on Illumination (abbreviated CIE for its French name, Commission internationale de l'éclairage) is the international authority on light, illumination, color, and color spaces. In 1976, the CIE developed the CIE L*a*b* (ΔE^*_{76} or ΔE^*_{ab}), which is a commonly used color space to evaluate color changes in dental resins.[17] It is also an ISO/TR 28642:2016 norm recommended reference.[5] CIE has refined their definition over the years due to the perceptual non-uniformities in the underlying CIELAB color space, leading to the superior 1994 (ΔE^*_{94}) and 2000 (ΔE^*_{00}) formulae.[43]

Among all studies included in this systematic review, ΔE^* calculation was conducted using two formulae, namely ΔE^*_{ab} and $\Delta E^*_{00.}$ However, ΔE^*_{ab} was more popular, with 29 studies using it; while ΔE^*_{00} formula was used in one study only; ΔE^*_{94} was used in none (Table 7). Certain conversions of systems were adopted by authors to yield clinical significance from the ΔE^* values obtained. The obtained ΔE^* values can be quantified by National Bureau of Standards (NBS) units to match the

color differences under clinical conditions, as adopted in eight studies.[8, 9, 11, 22, 31, 35, 39, 41] Scale defining thresholds for changes in color, namely the acceptability threshold and perceptibility threshold, were mentioned in 23 studies.[2, 10, 12-14, 16, 17, 21-32, 34, 35, 41, 44]

Translucency has been described with varied indices in literature, making it difficult for researchers and clinicians to find universal information on the translucency.[45] There are three general methods to quantify translucency of materials, total or direct transmission coefficient (t_c), translucency parameter (TP), and contrast ratio (CR). The transmission coefficient and CR indices each can be either luminous or spectral.[46] Measurements were made with instruments like spectrophotometer,[47, 48] colorimeter,[49] spectroradiometer,[50] and digital camera and software were reported.[51] The t_c is measured using a spectrophotometer with an integrating sphere that includes the scattered light. Translucency can be expressed as the relative amount of light passing through a material of specific thickness.[52] TP is the color difference of the same specimen over a white standard and a black standard background, and the range of the TP could be 0 to 100, calculated with the formula:

$$TP=\sqrt[2]{(L_w - L_b)^2 + (a_w - a_b)^2 + (b_w - b_b)^2}$$

where subscript "w" refers to the CIELAB values for the same specimen over the white background and "b" refers to the CIELAB values for the same specimen over the black background.[53] The CR value is calculated from the spectral reflectance of the specimens with black (Y_b) and white (Y_w) backgrounds. The equation for CR is defined as CR= Y_b/Y_w.[54] The CR value of a perfectly transparent material is 0, while the value of a completely opaque material is 1.[55, 56]

The calculated value corresponds directly to human visual perception of translucency.[53] All studies included in this review looked at color change of denture teeth, while only Imamura et al[32]

and Güth et al[36] investigated the translucency parameter. On the other hand, Roslan et al[7] looked at reflectance versus wavelength of artificial teeth. Besides translucency, fluorescence was of interest in one study, which was conducted by Güth et al as this parameter influences the visual appearance of dental restorations in the oral cavity.[36]

Surface appearance can change a person's perception of color. Therefore, the surface color of a material with different gloss value will need to be measured by different geometric conditions, namely the Specular Component Included (SCI) and Specular Component Excluded (SCE) conditions. Specular reflection is the mirror-like reflection of light waves from a surface. The SCI condition records true color data regardless of surface appearance; while the SCE condition is similar to color perception observed by the human eye, which is when the surface characteristics become part of the color one sees. This measurement was only conducted in one study, which was done by Gruber et al(2020)[17] that looked at ΔE^*_{ab} SCI and ΔE^*_{ab} SCE.[57]

Along with optical properties, several mechanical properties of denture teeth were being investigated in the studies included. Surface roughness and hardness were investigated in nine[8, 12, 13, 22, 23, 28, 34, 37, 42] and three[12, 22, 28] studies respectively. Four[21, 23, 32, 34] studies conducted scanning electron microscopy during the post-evaluation phase to characterise the surface morphology changes (Table 8).

Discussion

The effect of exposure to various solutions on the change in optical properties especially the color of denture teeth was investigated in the current study. The systematic review of literature on the topic identified four important influencing factors when evaluating the optical properties of the denture teeth; type of artificial teeth; type of immersion solutions; immersion period and/or aging protocol; method of measuring ΔE.

Type of artificial teeth

Porcelain teeth were identified to experience less color change after immersion in solutions compared to PMMA teeth.[11,31,35] Among various brands of PMMA teeth, Vita Physiodens (PMMA with microfillers) have the least staining potential after immersion in solutions;[29, 38] while Biotone interpenetrating polymer network (IPN) teeth (PMMA with highly cross-linked copolymers) have the most color change as shown in different studies.[12, 27, 30]

Maxillary anteriors were uniformly used across all studies, with the central incisor being the most common tooth selected as they provide the largest flat surface area for testing. Most studies reported a standardised shade for comparison of color change, with Vita tooth shade A2 being the most commonly used. A few studies looked at multiple shades of teeth.[25, 29, 41] One study looked at the comparison of stainability between lighter and darker tooth shades.[14]

A standardized shade is necessary for consistent comparison of color change. Besides that, Gregorius et al investigated denture teeth shades B1, A2, A3, A4 to compare the influence of chroma on color difference after staining and ageing.[29] It was found that the higher chromatic shades had larger changes in chroma and lesser changes in lightness and hue. Rosentritt et al investigated in vivo color stability of acrylic resin teeth in shades A3, A3.5, A4, B3, B4, C2, C3, D2 and D4 reporting that only shades C2 and C3 showed significantly higher ΔE^* values.[41]

12 studies did not specify shade of denture teeth used for their experiment.[7, 22, 24, 27, 30-32, 35, 37-40] However, it is critical to report the selected tooth shade for readers to be able to make a comparison with other studies. Also, it was found that a darker shade will undergo a larger degree of color change after immersion in cleaning solution than a lighter shade,[14] possibly due to a larger quantity of pigment in the teeth having a darker shade.

CAD/CAM milled denture teeth demonstrated comparable color stability to conventional denture teeth.[2] Color stability of 3D printed denture teeth compared to conventional denture teeth was inconclusive as the study done by Gruber et al showed more color change compared to conventional heat-polymerised and CAD/CAM denture teeth.[17] On the other hand, Koh et al found that color stability of 3D printed artificial teeth comparable to that of conventional artificial teeth after immersion in solutions.[16] 3D printed PMMA denture teeth with nanoparticles inclusion demonstrated higher color stability than 3D printed PMMA denture teeth without fillers.[21]

Immersion solutions

The most common staining beverages investigated, in descending order, were coffee, Coca-Cola, red wine and tea. Among all, the most staining beverage is coffee,[11, 25, 27, 31] while the least staining is tea.[26, 44, 58, 59] As shown in the two papers that looked at the effect of acidic beverages on artificial teeth, exposure to acidic beverages does have a significant effect on color change of artificial teeth.[12, 13] Another common immersion solution studied is denture cleaning agent. As shown in several studies, most denture cleaning agents cause color changes of denture teeth.[14, 25, 37, 40] Most studies found that all denture cleaners causes the color change of the same material to a similar extent, even though a study done by Moon et al found that Polident 3 minute denture cleaner causes the largest degree of color change, possibly due to its chemical composition.[25] On the other hand, liquid disinfectant soaps,[22] chlorhexidine 0.2%,[38] and neutral soap,[39] all were found to have low staining potential. Hence, liquid disinfectant soaps and chlorhexidine 0.2% can be used for cleaning dentures. Moreover, washing denture with soap and water is a recommended protocol for stain removal caused by coloring beverages.[10, 22, 39]

When looking at in vivo studies, according to Rosentritt et al, there is no significant association between consumption pattern and cleaning methods on the color change of denture teeth.[41] On the

contrary, Barao et al shows that there is association between color change values and staining solutions.[24]

Timeframe for color stability

The degree of staining is proportional to the period of immersion in most studies.[7, 27, 35, 41] However, Barzyk et al found that there is more staining in the initial period of immersion.[58] Thermal cycling, which is an artificial aging protocol is known to cause color change in denture teeth.[14, 23] However, Assuncao et al found that thermal cycling does not cause a statistically significant color change.[30] These contradictory observations might be attributed to other factors such as different teeth composed of varied molecular structure, color pigments and surface structure.[23]

Different durations of clinical use were investigated among the three included in vivo studies.[21, 24, 41] Despite this, the color changes in the experiments conducted by Cristache et al and Rosentritt et al were still considered clinically acceptable.[21,41] However, Barao et al found that the color changes were above the acceptability threshold.[24] Nonetheless, participants failed to notice it, which questions the current threshold of clinical acceptance of color change in denture teeth.

Method of measuring ΔE

Delta E (ΔE^*) is a standard measurement created by the CIE. The "E" in Delta E stands for "Empfindung," which is the German word for sensation. Delta is a Greek word that stands for the incremental change of a variable. As a whole, the term Delta E means a difference in sensation. ΔE^* is measured on a scale from 0 to 100, where 0 suggests least color difference, and 100 indicates complete distortion.[57]

The CIELAB color space is a three dimensional color space with three axes namely L*, a* and b*. It represents a uniform color space, with equal distances corresponding to equal perceived color

differences.[6] The CIEDE2000 is a more sophisticated formula that was developed to address perceptual non-uniformities. This is because the CIELAB space was apparently not perceptually uniform as intended, especially in the saturated regions.[60] It is important to note that ΔE* values calculated by different equations are not comparable to each other. The advantage of the CIELAB system is that color differences may be expressed in units that can be related to visual perception and have clinical significance.[6] CIELAB metric was more often used to calculate color difference than newer CEIDE2000 formula, even though the latter formula is more useful in the clinical context as the color differences calculated with the CIEDE2000 formula were better correlated with the differences perceived by the human eye.[61,62] This might be because this formula includes weighing functions and scaling factors of the parameters included in the formula.[63]

Moreover, the calculation of a color difference is of little clinical meaning without establishing the parameters that have some practical implication. In other words, the significance of color changes is important and can be done by assessing the value that is visually detected, known as the perceptibility threshold; and the value of color difference that most individuals would consider unacceptable, known as acceptability threshold. [9]

Based on the clinical thresholds described in the ISO/TR 28642 (64): the CIELAB perceptibility threshold (PT) is $\Delta E_{ab} = 1.2$, whereas the acceptability threshold (AT) is $\Delta E_{ab} = 2.7$. Corresponding PT and AT values are $\Delta E_{00} = 0.8$ and $\Delta E_{00} = 1.8$ for CEIDE2000.[64] On the other hand, some studies adopted ΔE^* values of more than 3.3 is considered clinically unacceptable.[1,12-14, 27, 28, 30-32,41] In the dental literature, a range of PT and AT values were established over the years by authors, as shown in table 9. Nevertheless, future studies should consider comparing ΔE^* values to AT and PT values to provide some comparative clinical context to the results.

The ΔE^* values was often used to evaluate the 'perceptibility' of color differences. As mentioned before, the criteria of perceptibility adopted by each author varies. Hence, the NBS rating system was used to determine the degree of color difference. ΔE* values can be converted to respective NBS units to match the color differences under clinical conditions.[8] This NBS rating system is based on how the human eye evaluates a color change, which is to determine what an observer may report regarding color changes of denture teeth after immersion in solutions in the context of this review.

The NBS units can be calculated using the formula: NBS Units = ΔE^* x 0.92.[8] This system offers absolute criteria by which ΔE^* values can be converted to remarks with clinical significance. NBS unit ranges between '0.0-0.5' to '12.0 - or more', and the critical remarks of corresponding color differences range from 'extremely slight change' to 'change to other color' respectively.[9] The clinically acceptable level is $\Delta E^* = <3.0$.[65, 66] This system is useful for an observer to easily report on his/her perception of color change.

Other parameters

Translucency is an important characteristic that affects the appearance of artificial teeth. Besides a good color match, translucency is a critical factor in the selection of materials to provide a natural look and light reflectance for dentures.[67] Fluorescence, which is the ability of a substance to emit light after absorption of light or other electromagnetic radiation, is also important for denture teeth since natural human teeth are fluorescent. Teeth looks aesthetically pleasing when exposed to these lights (for example natural sunlight and UV radiation, studio flashes) because they look whiter, livelier and shinier. Therefore, fluorescence in restorative materials is important as it provides a visual perception much closer to reality.[68] However, this property is rarely tested in denture teeth, which is seen in only one study.[33]

Surface roughness and hardness were tested in nine[8, 12, 13, 22, 23, 28, 34, 37, 42] and three[12, 22, 28] papers respectively along with optical properties. However, it is actually important to not only investigate the optical properties, but also the mechanical properties such as hardness to give an overall understanding and to demonstrate the relationship between optical properties, surface mechanical properties and biological considerations (e.g. biofilm attachment). Studying specimens under scanning electron microscopy (SEM) was often conducted in the past studies to observe the changes in surface characteristics of materials at a microscopic level.[69] It is beneficial as some trends observed from the experimental results can be correlated to the properties of material, such as the size of particles and material composition. However, only four studies conducted this, [21,23,32,34] possibly due to SEM being an expensive testing equipment that is often not accessible to researchers.

Conclusion

The following conclusions were drawn from the findings of the present systematic review: Color stability of CAD/CAM milled denture teeth is comparable to conventional PMMA denture teeth. There is contradictory findings in terms of color stability of 3D printed denture teeth as compared to conventional PMMA denture teeth. Denture teeth can show color changes after immersion in staining beverages as early as one week. The degree of discoloration of denture teeth after immersion is time dependent, with the larger extent in the initial phase. Staining by coffee is worst among the common beverages and solutions investigated, hence recommendations can be made for denture patients to avoid the consumption of coffee to minimize staining of denture teeth.

Recommendations

Some recommendations can be made for future studies wanting to study optical properties of denture teeth:

1) Porcelain teeth can be excluded for future studies as they are not used in modern denture fabrication.
2) Apart from staining beverages, other solutions commonly used by denture wearers such as denture cleaning agents should be included in future studies to test the optical properties of denture teeth.
3) The CIEDE2000 color difference formula should be considered for use in clinical instrumental color analysis, rather than the traditional ΔE^*_{ab} for more accurate interpretation of color changes.
4) Instead of merely reporting subjective changes of color change in terms of shade, color difference formula should be used to calculate color change and reported in numerical value for a more accurate measurement of color stability.
5) Translucency parameter can be conveniently reported since the values of each parameters are readily available during shade measurement using a spectrophotometer.
6) Future studies should include the measurement of fluorescence of artificial teeth in relation to natural teeth.
7) Post-test analysis (e.g. surface roughness or hardness or image analysis) is recommended for future studies on color stability to draw meaningful interpretation of the observed trends.
8) More studies are required for digitally manufactured denture teeth — CAD/CAM milled and 3D printed denture teeth.

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Figure Caption

Figure 1. PRISMA flow diagram of the study selection process of optical properties of denture teeth.