tooth color and tooth discoloration

in-vitro studies on tooth color determination
and tooth discoloration related to endodontic procedures

tina van der burgt

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PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE GENEESKUNDE AAN DE KATHOLIEKE UNIVERSITEIT TE NIJMEGEN, OP GEZAG VAN DE RECTOR MAGNIFICUS PROF. DR. J.H.G.I. GIESBERS VOLGENS BESLUIT VAN HET COLLEGE VAN DEKANEN IN HET OPENBAAR TE VERDEDIGEN OP VRIJDAG 20 DECEMBER 1985 DES NAMIDDAGS OM 2.00 UUR PRECIES

DOOR

TINA PATRICIA VAN DER BURGT

GEBOREN TE NAARDEN

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VOORWOORD

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CONTENTS

GENERAL INTRODUCTION

The esthetic appearance of the dentition is of serious concern to most persons (Linn 1966; Linn 1976). A discoloration of teeth will influence the appearance of the dentition. In particular, stained anterior teeth can present a serious cosmetic problem.

Tooth discolorations are classified as extrinsic or intrinsic depending on the localisation (Spouge 1973). Extrinsic discoloration is characterized by stain accumulation on the tooth surface. Intrinsic discoloration affects the internal structures of teeth. When etiology is used as a classification basis, the discoloration of teeth is caused by endogenous or exogenous factors (Spouge 1973). Endogenous pigments are produced by the body itself, whereas exogenous pigments are derived from outside the body.

Extrinsic tooth discoloration has been investigated extensively. The mechanisms involved in the development of extrinsic discoloration are: chromatogenic bacteria, retention of colored substrates, and chemical transformation of pellicle components (Eriksen 1978). Extrinsic discolorations can easily be removed by mechanical means.

Intrinsic tooth discoloration may appear before as well as after completion of tooth formation (Vogel 1975). Hereditary and congenital defects can induce intrinsic discoloration of developing teeth (Pindborg 1970). Drug administration and excess of fluoride intake during the odontogenesis, may result in a disturbing discoloration of teeth. Traumatic injuries, carious decay, and iatrogenenic factors, are the main causes of intrinsic discoloration after completion of the dentition (Ingle 1976; Rakow 1976; Nicholls 1977). The elimination of intrinsic discolorations is rather difficult. Sometimes improvement of the color can be achieved by bleaching, however frequently it is decided to cover stained anterior teeth with a full crown. In view of this, intrinsic discolorations should be prevented where possible. Iatrogenic stains due to the use of discoloring materials, can be controlled by the dental practitioner. So is amalgam contra-indicated to restore front teeth since it will result in almost predictable grey stain (Cohen 1984). Also several endodontic drugs and filling materials are suspected to produce moderate to severe tooth discoloration (Goerig 1974; Nicholls 1977). A review of the literature, however, did not reveal any study on the staining properties of current endodontic materials. Therefore, it is difficult for the dentist to select non-staining materials for a root canal treatment.

The aim of the present study is to investigate systematically the staining potentials of dental materials, that are generally used in endodontics. For research on tooth discoloration, a reliable method for tooth color determination is essential. In part I of this thesis, the optical processes that influence the color of a tooth are discussed. Based on the acquired understanding, two methods for tooth color quantification are developed. Part II deals with tooth discoloration related to endodontic therapy. An in-vitro technique for inducing intrinsic tooth discoloration is developed. Using this technique, a number of experiments is performed on the staining of tooth crowns caused by dental materials.

Note: The fact that several chapters will be/are published in seperate papers in different journals, made it inevetable that some sections in a number of chapters are repetative in nature.

COLOR AND COLOR DETERMINATION

I.1.1. INTRODUCTION

For investigations on tooth discoloration, a suitable method for tooth color determination is a prerequisite. To define criteria for selecting such a method, the phenomenon of tooth color should be well understood. For this purpose, a literature study is undertaken regarding the optical processes that effectuate the color of an object. The various methods for determining the color of an object, are evaluated as well. In addition, attention is payed to the different coordinate systems to express the color of an object.

The information acquired from the general discussion on color, is combined with the specific optical problems in dentistry. Based on this knowledge, an attempt is made to formulate criteria for a proper method for tooth color determination.

I.1.2. COLOR PERCEPTION

Color stimulus

The color is not a physical property of an object, but the visual effect of lightwaves entering the eye after being modified by the object (Billmeyer 1981). This implies that color perception depends on physical, physiological, and psychological processes. The color ascribed to an object is determined by the combined effect of the lightsource, the object, its environment, and the detection and interpretation by the observer.

Light is electromagnetic energy, qualitatively defined by the wavelength. Visible light consists of wavelengths between 380 and 750 nanometer, which is only a small section of the entire radiation spectrum that includes X-rays and radiowaves.

Incident light stimulates the retina of the eye. The degree of stimulation is related to the wavelength and the intensity of the light. In the retina the light is converted into electrical impulses. These impulses are conducted by nerve bundles to the cerebral perception centre, where they induce a color sensation. Figure 1 illustrates the range of visible light with the associated color sensations.

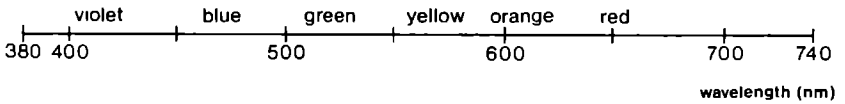

FIGURE 1:
Visible light with associated color sensations.

Lightsource

Usually a lightsource emits light at different wavelengths, as can be demonstrated with a prism. A lightsource is characterized by the amount of energy radiated for each wavelength. A grafical plot of this quantity forms the spectral energy distribution curve of the lightsource. For many applications, knowledge about the full curve is not needed. Then the color temperature of the source may be used. This is the temperature of a 'black body' having the same color as the lightsource.

Ideally, white light emits equal amounts of energy for each wavelenght in the range of visual light. Natural daylight contains relatively much blue light and is rather dependent on the time of the day and year and the atmospheric circumstances (Billmeyer 1981). The spectral energy distribution curves of most conventional fluorescent tubes, show narrow extremes due to exitation of gas molecules, atoms or ions.

The 'Commission Internationale d'Eclairage' (CIE 1971) defined standard lightsources A, B, C, and D_{65} having associated color temperatures of $2854^{o}K$, $4870^{o}K$, $6770^{o}K$, and $6500^{o}K$, respectively. Illuminant A is comparable to a tungstun lamp, illuminant B resembles noon-sunlight. Lightsources C and D_{65} approximate diffuse daylight.

Object

Illuminating light is partly reflected at the surface of the object and partly penetrates into it. Illumination of a rough surface induces diffuse reflection, as a result of which the surface seems to be dull. At a smooth surface, the reflection is both diffuse and specular, giving the object a glossy appearance (figure 2).

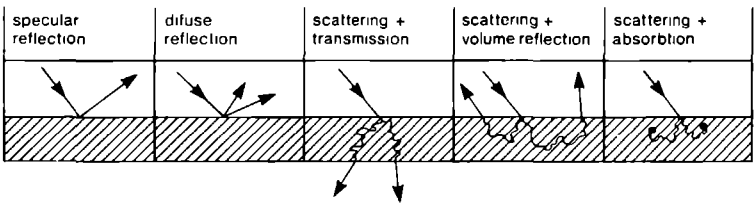

FIGURE 2:
Optical processes in translucent materials.

Light entering the object bends off at the surface due to a change in refractive index, unless the light hits the object perpendicularly. After entering the material, light will be transmitted, absorbed, and scattered (figure 2). These physical properties determine whether an object appears to be transparent, opaque, or translucent. Transmission means that light passes through the material, whereas absorption refers to the process of light disappearing in a material. When light is scattered in a material, it undergoes multiple directional changes. Scattering occurs in materials that contain particles, provided the refraction indices of the particles and the carrier material are different. In addition, the size of the particles must be of the order of the wavelength of the entering light or smaller.

As a result of scattering, incident light may leave the material through the illuminated surface, usually at another place (figure 2). This phenomenon is called volume reflection (CIE 1977). When gloss is avoided, the majority of light reflected from objects is usually due to volume reflection. The average distance, traversed by light in a material, is related to the absorption and scattering coefficients of the material, which in their turn depend on the wavelength of the light.

The reflectance of an object is determined by the combined effect of surface reflection, transmission, absorption, and scattering. The spectral transmission or reflection curve of an object, expresses for every wavelength the percentage of light transmitted or reflected. The color under 'white light' illumination is related to the dominant wavelength of

this curve. Objects with a horizontal reflection curve appear to be white, grey, or black depending on the amount of light reflected.

Apart from the spectral reflection curve, the color of an object is influenced by: turbidity, gloss, fluorescence, surface character, size, background, environment, etc.

Detector

The relative sensitivity of a detector for each wavelength of visble light, is reproduced in the spectral response curve. Light detectors are not equally sensitive for each wavelength, which is illustrated by the several kinds of detectors (rods and cones) in the retina of the human eye. A specific response curve is associated to each of the 3 types of cones. Together, the cones allow the eye to sense color properly within the range of visible light. Even in very dim light the rods are exitated, but they do not impart color vision.

Other important light detectors are photomultiplier tubes and silicon photodiodes, which respond differently to different wavelenghts. The response curve of both photo-electric detectors is unlike that of the human eye.

The resulting color stimulus is achieved from the spectral energy distribution curve of the lightsource, the spectral reflection curve of the object and the spectral respons curve of the detector, as indicated in figure 3.

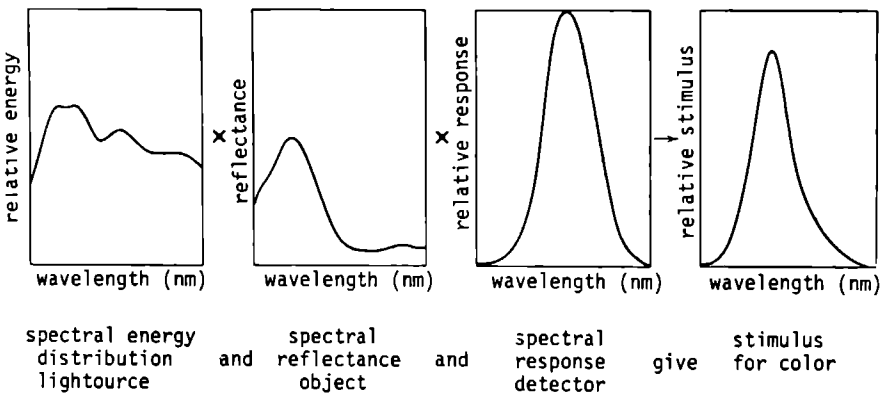

FIGURE 3:
The color perceived of an object is determined by the interaction of light source, object, and observer (from Billmeyer 1981; with permission of John Wiley & Sons, New York, USA).

Metamerism

Sometimes the color of 2 objects is similar using a certain lightsource, whereas their colors are clearly distinct using other lightsources. This phenomenon is referred to as metamerism and is illustrated in figure 4 (Billmeyer 1981). Although metameric objects have different reflection curves, the same color stimulus may be obtained for a certain illumination. One should always be aware of metamerism, unless the objects are identically composed. To avoid errors due to metamerism, various lightsources should be employed in comparing the color of objects.

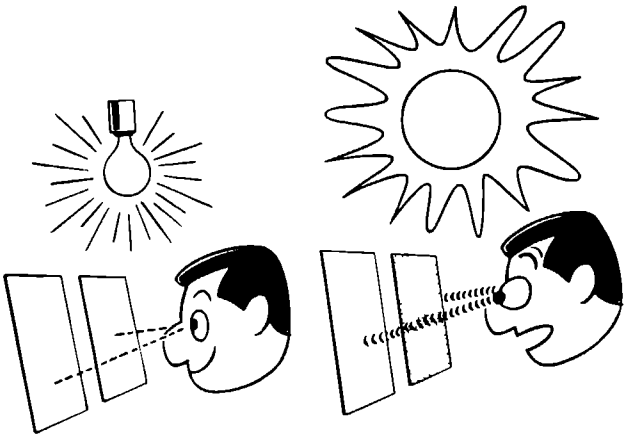

FIGURE 4:
The phenomenon of metamerism (from Billmeyer 1981; with permission of John Wiley & Sons, New York, USA).

I.1.3. COLOR CLASSIFICATION

Munsell color order system

In the Munsell color order system, colors are numerically arranged according to the 3 visually distinguishable color dimensions: Hue, Value, and Chroma (Munsell 1961). The system of color distribution is demonstrated in figure 1 chapter II.4. Hue is shade or color tone (red, blue, green, etc.) and is related to the dominant wavelength in the reflection curve of the object. Value is the degree of grey or brightness, varying between black and white. The term Chroma indicates the saturation of a color.

The Munsell system is a collection of colored samples spaced in 3 dimensions. Between adjacent samples the interval of visual perception is equal. Each sample carries a Munsell notation denoting its position. This notation consist of 3 symbols representing the Munsell Hue, Value, and Chroma, respectively.

XYZ tristimulus values

The CIE (1971) defined the color of an object, illuminated by a standard lightsource and observed by a standard observer, in the tristimulus values X, Y, and Z. The standard observer's color perception was derived from the average spectral response curve of the human eye.

The classification in tristimulus values is based on the principle of additive color mixture. The color of the light from a lightsource can be matched by mixture of 3 different colors of light in the right proportion. These 3 colors, for example blue, green, and red, are referred to as the primaries. The quantities of each primary, required to match a certain color of light, together form the tristimulus values of that color. Using realistic primaries, some light colors can only be matched when negative tristimulus values are introduced. To avoid these negative values, 3 other primaries X, Y, and Z are developed, having imaginary spectral distribution curves. Each color of light can now be expressed in positive

amounts of X, Y, and Z. For each wavelength, the relative amount of X, Y, and Z is described in the standard observer's color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ (figure 5).

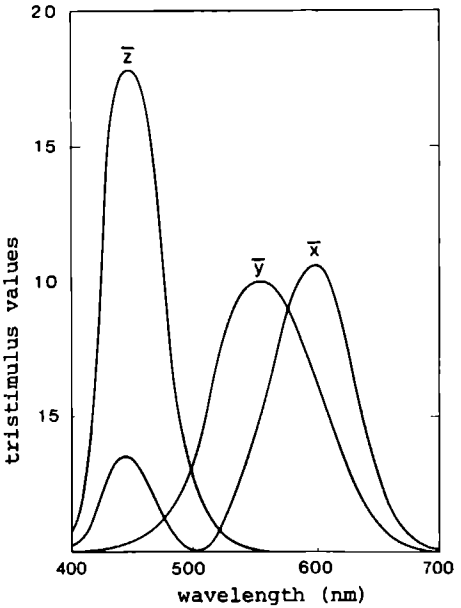

FIGURE 5:
The color matching functions $\bar{x}$, $\bar{y}$, and $\bar{z}$ of the 1931 CIE standard observer (from Billmeyer 1981; with permission of John Wiley & Sons, New York, USA).

The color of an object results from the normalized spectral energy distribution curve of the lightsource (E) and the spectral reflection curve of the object (R). The amount of light reflected from the object for any wavelength λ is $E(\lambda).R(\lambda)$. The CIE tristimulus values are calculated by integration over the visible wavelenghts of the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ functions, multiplied by the spectral distribution curve of the lightsource and the reflection curve of the object.

$$X = E.R.\bar{x}\, d\lambda \qquad Y = E.R.\bar{y}\, d\lambda \qquad Z = E.R.\bar{z}\, d\lambda$$

The color of an object is often expressed in the CIE coordinate system (Y, x, y), in which x and y are the chromaticity coordinates. Y is the perceived lightness, x and y describe the chromatic dimensions of the color.

$$x = {}^{X}/_{X + Y + Z} \qquad y = {}^{Y}/_{X + Y + Z}$$

Uniform color spaces

A clear disadvantage of the CIE system is the fact that visually it is not spaced equally. It is difficult to relate the coordinates X, Z, x, and y to visually perceived color dimensions; only Y is easily to be interpretated because of its high correlation with brightness. Furthermore, the distance in the coordinate system between 2 colors that are just distinguishable, is not the same for all colors.

Various alternative color scales have been developed to avoid these problems. Hunter (1975) listed a number of such uniform color spaces and described the inter-comparison and relationship between the major scales. Each scale includes a special color difference formula to quantify color

differences. The CIE (1976) recommended the use of 2 approximately uniform color spaces with their associated color difference formulae: the CIELAB and the CIELUV color space. The CIELAB is a non-linear transformation and the CIELUV a linear transformation of the CIE system; colors are expressed in the coordinate systems (L*, a*,b*) and (L*, u*, v*), respectively. In addition, guidelines are given to convert L*a*b* and L*u*v* data in terms of Hue, Value, and Chroma. Quantitatively, these terms do not correspond to Munsell's Hue, Value, and Chroma.

I.1.4. COLOR DETERMINATION

Visual

Visual determination of the color of an object, is based on visual comparison of the object with color standards. The object and the standard are viewed simultaneously and under the same, preferably standardized, lighting conditions. Although the eye is well suited to match colors, specification of the magnitude and direction of the differences can not be done in a reliable way.

Instrumental

Using optical instruments, the color of an object is assessed by analyzing the light reflected from the object. The amount of reflection is compared to the 100% reflection from a white reference surface. Usually, gloss from the sample surface is excluded from the measurements by means of a gloss-trap.

Instrumental color determination can be devided into 2 main cateories: instruments using 3 colored lights and those using monochromatic light. Monochromatic light contains only a narrow wavelenght of the spectrum. Using a colorimeter, the sample reflectivity is measured subsequently with 3 different kinds of light. By proper selection of these lights, the reflection readings are equal to the CIE tristimulus values under a single, specific illumination; or they are converted into those values by simple equations. With a spectrophotometer, the object reflectivity is analysed using monochromatic light of all visible wavelengths successively. The spectral reflection curve from the sample is constructed from the reflection data. This curve contains all information needed to calculate the color of the sample for any lightsource and observer.

Nowadays, most optical instruments are equiped with photo-electric detectors. The intermediate form between visual and instrumental color determination, is examplified by the Lovibond (Tintometer, Salesbury, UK). This instrument is a fiber optic colorimeter using the eye as detector.

I.1.5. TOOTH COLOR DETERMINATION

Optical considerations

A tooth is to be considered as a double layered structure. The inner layer is the intensely colored and rather opaque dentin. The dentin is covered by enamel, which is a fairly colorless and translucent material. The color of the dentin shows through the enamel. In endodontically discolored teeth, for example, the color of the dentin has changed (Vogel 1975), which is visible at the external tooth surface.

The interaction between incident light and a tooth is complicated. It includes: surface reflection, absorption, transmission, and scattering (ten Bosch 1981). Because of the scattering of light in the enamel layer, volume reflection is induced (see page 10).

For clinical studies on tooth color it is desirable that the color readings performed on teeth, concur the clinical impressions. In other words, the data obtained should be as much as possible in agreement with the tooth colors as perceived visually. The occurence of volume reflection in the enamel, will interfere with the tooth color measurements, unless the lighting and viewing conditions are properly adapted. Theoretically, removal of the enamel layer would facilitate the evaluation of intrinsic tooth discoloration related to endodontic treatment. This suggestion, of course, is not acceptable for clinical discoloration studies. Similar problems due to volume reflection, are involved in skin color measurements (van Oort 1981). The solution was found in enlargement of the skin region used for the reflection measurements. Large window measurements, however, cannot be applied in dentistry since the size of a tooth crown is too limited.

An additional difficulty is that teeth happen to be localized in the oral cavity. Using conventional optical instruments, objects are analyzed seperately inside the instrument, which is not possible in clinical studies.

Summarizing, the facts that a tooth is small, partly translucent, and placed in the mouth hinder its color determination and even its color definition.

Criteria for tooth color determination

Considering the literature review on color and in view of the specific dental problem, it is concluded that a method for tooth color determination should meet the following requirements:

* The method is reproducible.
* The method is simple and needs little operator time.
* The data obtained can be expressed in CIE color specifications.
* The method takes into account the optical properties of teeth.
* The information obtained is clinically relevant.
* The measurements are non-destructive.
* The method can be adapted for intra-oral use in clinical situations.
* Minor color differences can be detected using the method.

OPTICAL PROBLEMS OCCURING IN REFLECTION MEASUREMENTS ON TRANSLUCENT MATERIAL[1]

T.P. van der Burgt and J.J. ten Bosch* (University of Nijmegen and *University of Groningen, The Netherlands)

I.2.1. INTRODUCTION

Using optical instruments, the color of an object is determined by analyzing the light reflected by the object. When gloss is avoided, usually the majority of the reflected light is due to volume reflection. Volume reflection or backscattering is caused by light scattering inside the material. As a result of volume reflection incident light enters and, at a different place, leaves the material through the illluminated surface (CIE 1977). The average distance light traverses in a material, is related to the absorption and scattering coefficients of the material, depending in their turn on the wavelength of the light. This effect has been calculated and measured (Groenhuis 1983a and 1983b). In translucent materials this average distance is in the order of mm's; in opaque materials it is small compared to visually distinguishable distances. The large sideward distance light traverses in translucent objects, probably disturbs its color determination (ten Bosch 1985). When this distance approximates the size of the object (as is the case with teeth), reflectance measurements may be expected to be subject to large errors.

To affirm the importance of this theory, the color of a number of translucent plastic samples is evaluated spectrophotometrically using a small, medium, and a large window diameter, respectively. The results obtained with the 3 windows are compared.

I.2.2. MATERIALS AND METHODS

Translucent samples

Eighteen homogeneously colored, translucent plastic slabs were used. The thickness was between 3.2 mm and 6.3 mm. To estimate the relative translucency of the samples, their center was perpendicularly illuminated with white light from a fiber with a diameter of 1.5 mm (ten Bosch 1985). A small (0.4 mm) fiber with a photodiode (HUV 1100B, ECG, USA), was used to determine the distance from the center to the circle where the illuminance was 10% of the maximum illuminance (figure 1). The distance found, referred to as spot-size, was considered to be a parameter for the translucency.

During the color evaluations, the slabs were placed on a black background. The surfaces to be analysed were glossy finished.

Spectrophotometric analysis

The samples were analysed using a spectrophotometer (RFC-3, Zeiss, Erlangen, BDR) with a window diameter of 5 mm, 15 mm, and 30 mm, respectively. For each window, the spectrophotometer was calibrated on a white and a black standard. Gloss from the sample surfaces was excluded from the measurements.

From the reflection spectra obtained, the XYZ tristimulus values were calculated for 2^{o} standard observer and for standard lightsource C (Driscoll 1978; Billmeyer 1981). To facilitate visual interpretation, these physical data were transformed into coordinates $L^* u^* v^*$ in the approximately uniform CIELUV color space (Hunter 1975). L* indicates the

[1]To be submitted to Applied Optics

brightness of a color. The index u* is related to redness (+) versus greenness (-); v* is related to yellowness (+) versus blueness(-). Color differences ΔE were computed using the CIELUV color difference equation:

$\Delta E_{uv} = ((\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2)^{1/2}$ (CIE 1976).

The L*u*v* data can also be expressed in terms of Hue, Value, and Chroma. The Hue or color tone is related to the index arctan (v^*/u^*). Value or brightness is associated to L* and the index $(u^{*2}+v^{*2})^{1/2}/L^*$ corresponds to Chroma or saturation (CIE 1976).

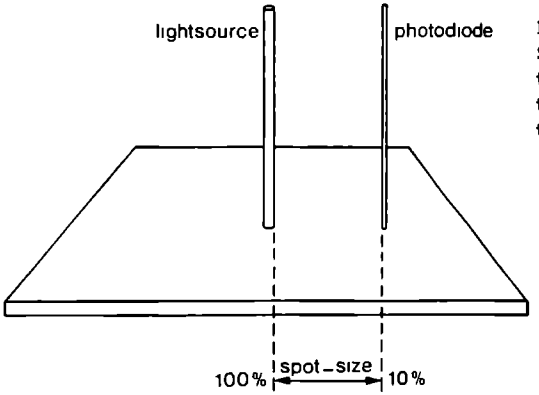

FIGURE 1:
Schematic representation of the method used to assess the translucency (spot-size) of the samples.

I.2.3. RESULTS

Figure 2 illustrates the reflection spectra of several samples measured with 30 mm window (large symbols), 15 mm window (without symbols), and 5 mm (small symbols), respectively. The size of the window seems to influence the level as well as the shape of the reflection spectrum obtained from a sample.

The L*u*v* data of a number of translucent samples, as calculated from the reflection spectra, are plotted in figures 3 and 4. Data from other samples showed similar behavior, but they were omitted for reasons of clearity. Large symbols refer to large window measurements (30 mm diameter), small symbols to small window measurements (5 mm diameter). The large and small symbols related to the same sample, are connected by a straight line, on which the spot-size of the sample is given. The results indicate that different color coordinates are obtained from the same sample using a small or a large window.

For each sample, the difference between the colors (ΔE) obtained with the 30 mm and 5 mm window diameter are outlined in figure 5 vertically. The relative sideward displacement of light around an illuminating fiber (spot-size) is shown in figure 5 horizontally.

In figures 2 to 5 a certain symbol is associated always to the same sample.

I.2.4. DISCUSSION

The color of an object is usually analysed with the same window for illumination and collection of the reflected light. The entering photons may be volume-reflected so far inside the material, that they emerge beyond the boundary of the window and thus become excluded from the measurement.

This phenomenon is referred to as edge-loss. Edge-loss is related to the average distance light traverses inside a material, which depends on the translucency and the color (absorption) of the material and the wavelength of the illuminating light. Blue light (short wavelength) is scattered more strongly than is red light (long wavelength), as a result of which red light penetrates further inside the material. This implies that the longer the wavelength of the light, the more important the edge-loss.

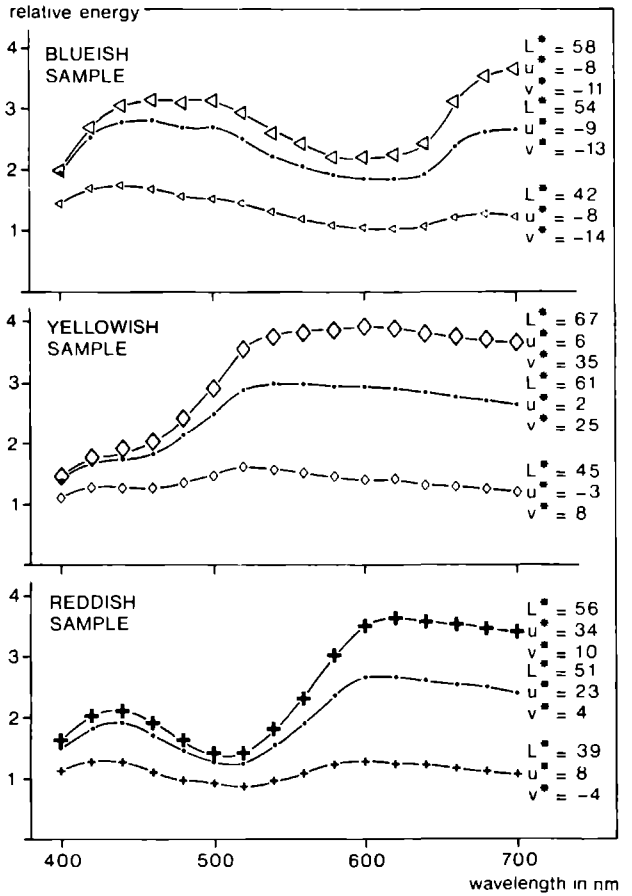

FIGURE 2:
Reflection spectra of translucent plastic samples determined spectrophotometrically with 30 m window (large symbols), 15 mm window (without symbols), and 5 mm window (small symbols). The associated L*u*v* data are also shown.

For a proper color determination, light losses have to be negligable. To prevent edge-loss, the window diameter should be large compared to the sideward displacement of the photons.

The effect of edge-loss is illustrated in the different reflection spectra, which were found with 30 mm, 15 mm, and 5 mm window diameters, respectively (figure 2). Using the 15 mm and 5 mm windows, the entire

reflection curves shifted towards a lower level as compared to the 30 mm window measurements. The level of the reflection curve is associated with the Value or brightness of the sample. Thus, the brightness L* decreases with the window diameter (figure 3). Relatively, the reflectance at long wavelengths decreases more than at short wavelengths. This is consistent with the wavelength dependence of scattering. As a result, the reduction of the window diameter also induced an alteration of the shape of the curves (figure 2) and thus an alteration of the perceived Hue and Chroma of the samples (figure 4). As the spectral decrease is relatively less at short wavelengths than at long wavelengths, a blue shift of the Hue may be expected when the window size is reduced. This is in agreement with the Hue changes shown in figure 4. The variation in Chroma or saturation (figure 4), seemed to be related to the original (large window) color of the sample. Most samples lost Chroma using the small window, whereas blue and greyish samples gained Chroma. The Hue, Value, and Chroma differences observed between large and small window measurements, can probably all be explained

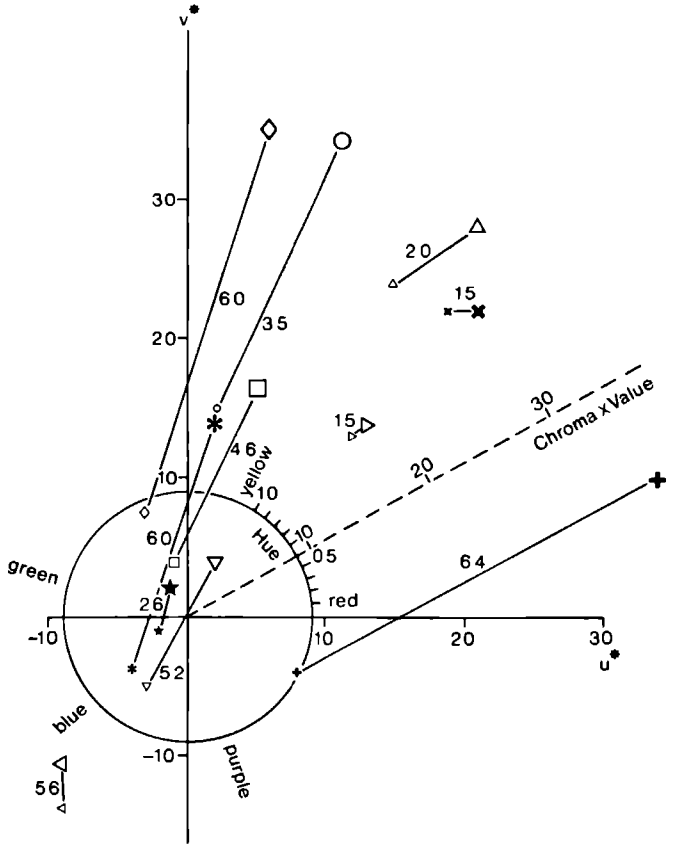

FIGURE 3:
u* versus v* (with Hue and Chroma x Value) of translucent plastic samples measured spectrophotometrically with 30 mm window (large symbols) and 5 mm window (small symbols). The spot-size is given on the line connecting associated symbols.

from a complete theoretical analysis of edge-loss and its wavelength dependence.

Figure 5 demonstrates the relation between the translucency of the sample and the color difference obtained with 30 mm and 5 mm window measurements, respectively. The translucency of the material seems to be a parameter in predicting the magnitude of the color difference, though other factors apparently play a role as well. Further investigation of these factors is necessary. In future studies on this subject, 2 major imperfections should be eliminated. First, the method employed to assess the translucency of the samples is optically incorrect, because the measurements are disturbed by the color of the samples. Another, more advanced technique should be used for analyzing the samples, to obtain reliable data on their translucency. Second, the color readings in the present study are influenced by the variation in thickness of the samples and the background on which the samples are measured. To obtain information, that exclusively concers the color, the experiment should be repeated with samples of 'infinite' thickness.

The optical properties of dental enamel, resemble those of the most translucent samples evaluated in the present study. In view of this, might be expected that similar optical problems are involved in traditional color measurements on teeth (using a small window for illumation and collection of the reflected light. Accordingly was decided to develop an alternative and simple method for tooth color determination, in which these problems do not occur (chapter I.3.).

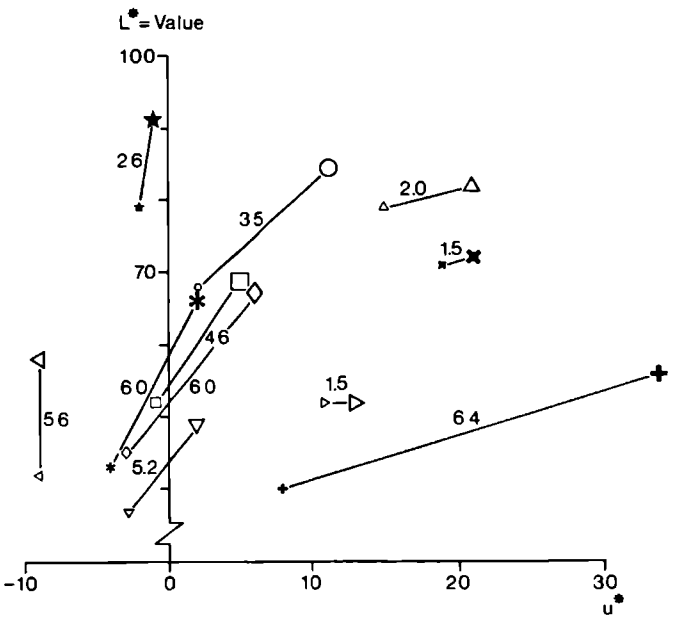

FIGURE 4:
L* versus u* (with Value) of translucent plastic samples measured spectrophotometrically with 30 mm window (large symbols) and 5 mm window (small symbols). The spot-size is given on the line connecting associated symbols.

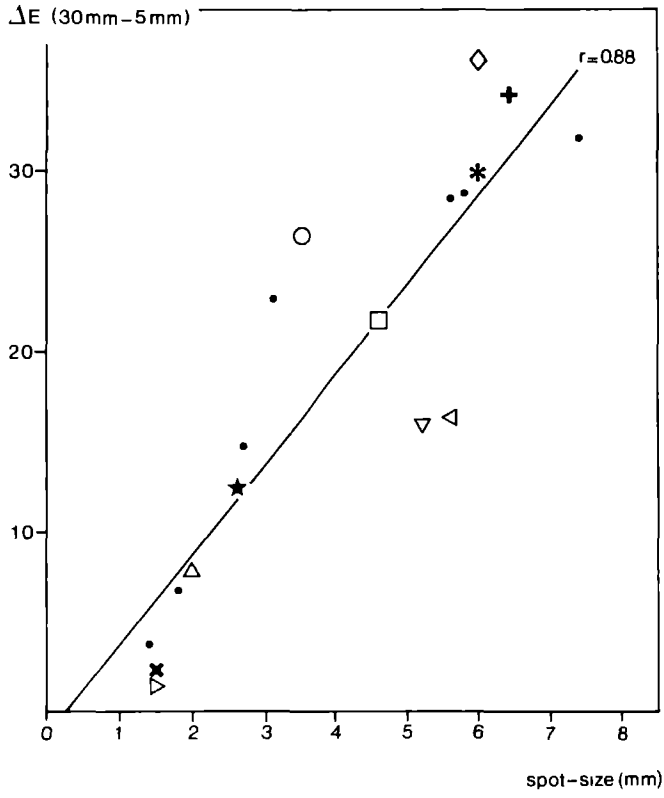

FIGURE 5:
Differences between colors (Δ E) measured spectrophotometrically with 30 m and 5 mm windows as a function of the size of the spot of the volume reflected light. The linear regression line and the correlation coefficient are shown.

A NEW METHOD FOR MATCHING TOOTH COLORS WITH COLOR STANDARDS[1]

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I.3.1. ABSTRACT

A new method for quantitative intra-oral tooth color determination is presented. Basically, the tooth color is assessed by visual comparison with opaque color standards, which are logically arranged according to 3 visual color dimensions. The standards were analyzed spectrophotometrically and the CIE color coordinates were computed. Illumination and observation were standardized during the matching procedure. Two distinct situations, method 1 and method 2, were investigated. The situation in method 1 is to be considered as large window illumination and small window collection of the reflected light. For method 2, the same small window was used for both illumination and observation.

Using both methods, the color of a tooth could be quantified into 3 separate color dimensions. Using method 1, the consistency between 25 examiners was high in determining the color of 10 teeth; using method 2, the inter-examiner agreement was low. For the same tooth, different color standards were selected with method 1 or method 2. The standard selected with method 2 often appeared to be in disagreement with clinical expectations. The differences in results between method 1 and method 2 are explained by the optical properties of the translucent dental enamel (e.g. volume reflection).

Method 1 allows for reproducible quantification of clinical tooth discoloration according to CIE color specifications and can possibly be applied in prosthetic dentistry.

I.3.2. INTRODUCTION

To analyze the color of an object, 2 general methods can be distinguished: visual and instrumental (Billmeyer 1981).

Visual color determination is based on visual comparison of the object with color standards. This method is most frequently applied in dentistry. Prosthetic shade guides commonly serve as color standards with which the color of a tooth is matched. Nevertheless, 3 distinct disadvantages concerning this method are reported: First, the range of available shades in the shade guides is inadequate. In addition, the shades are not logically distributed (Sproull 1973). Second, there is a lack of consistency among and within individual dentists in matching tooth colors (Culpepper 1970; Barna 1981; O'Neal 1984). Third, it is not possible to translate the results obtained into CIE (Commission Internationale de l'Eclairage, Paris, France) color specifications. Apart from prosthetic shade guides, more logically arranged sets of color standards were used to determine the color of teeth in dental research (Clark 1931; Hayashi 1967). The standards were kept adjacent to the tooth to be matched. In those studies, no special attention was payed to the reliability of the matching procedure itself.

When optical instruments are used, the color of an object is determined by analyzing the light reflected by the object. Several attempts have been made to establish the color of teeth instrumentally (Ishikawa 1969;

Sproull 1973; Grajower 1976; MacEntee 1981). The regions of the color space in which the tooth colors were found, however, differed significantly among various investigators (MacEntee 1981).

A major limitation of most studies concerning reflectance measurements on teeth, is the fact that the optical properties of translucent materials, such as dental enamel, are not properly taken into account (Hunter 1975; ten Bosch 1984).

Summarizing, it can be concluded that, at present, no reliable method for tooth color determination or even color comparison is available. The purpose of this study was to describe and test a new method for quantitative tooth color comparison, based on the physical-optical processes occurring in tooth structures.

I.3.3. MATERIALS AND METHODS

Samples

Humidity controlled, extracted human upper incisors were used. The teeth were selected visually to cover a wide range of natural tooth colors. To prevent discoloration of the tooth crowns during the study, the external tooth surfaces were mechanically cleaned and pumiced. Furthermore, the pulps were extirpated and the pulp cavities were cleaned using suitable endodontic instruments.

Color standards

The collection of color standards consisted of opaque cardboards (22 x 40 mm; from Sikkens Color Collection 20/21, Sikkens, Sassenheim, The Netherlands), arranged according to the 3 visual color dimensions: Hue, Value, and Chroma (Munsell 1961). Hue is shade or color tone e.g. red, yellow, blue, etc. Value is the degree of grey or brightness. The term Chroma indicates saturation or intensity (figure 1 chapter II.4). The cartons were glossy finished with a 30 % polyvinylalcohol solution.

Using a spectrophotometer (Hunterlab Spectrophotometer D54P-5, Hunter Associate Laboratory, Reston, USA), every color standard was analized. CIE color specifications X, Y, and Z were computed from the reflectance curves obtained (Driscoll 1978). The calculation was performed for standard lightsource D_{65}, 2^{o} standard observer (Billmeyer 1981), and included gloss correction. Subsequently, the XYZ data were converted to coordinates L*, u*, and v* of the approximately uniform CIELUV color space (Hunter 1975). Color standards with $55 < L^* < 91$, $2 < u^* < 63$, and $5 < v^* < 56$ were used.

To facilitate interpretation of these physical color specifications, all data were expressed in terms of Hue, Value, and Chroma (CIE 1976). Hue is related to the index $\arctan(v^*/u^*)$, Value is associated with L*, and the index $(u^{*2}+v^{*2})^{1/2}/L^*$ corresponds to the Chroma.

In the set of color standards, basically, 7 aproximately equidistant Hue, 8 Value, and 6 Chroma steps could be distinguished. The size of the intervals between the individual steps was about 0.1 for Hue, 5.0 for Value, and 0.12 for Chroma. The collection was not fully complete for all possible combinations, mainly because the standards were alternately arranged for Value and Chroma.

Illumination

Background and environment were standardized and of neutral colors. The tooth to be examined was placed in the front region of the dental arch of a phantom head. The observers were dressed in white coats.

The samples were illuminated by daylight fluorescent tubes (TL-47,

Philips, Eindhoven, The Netherlands), whereas additional light from other sources was excluded. The lighting intensity was 1500 Lux at the tooth surface.

Observation

Observers were dentists or dental students, whose color vision was found to be normal by the 100 Hue Farnsworth-Munsell test. After explaining the system of color ordering, the observers were asked to make the best match with the set of color standards.

The color of the mid-cervical part of the labial tooth surface, was matched with that of a color standard which was held adjacent to the labial tooth surface. The tooth and the standard were viewed simultaneously through 2 holes (diameter 4 mm; 6 mm apart) in a neutral grey shield. The shield (15 x 35 mm) was kept parallel to the tooth surface (figures 1 and 2).

The viewing distance was about 25 cm. With respect to their angle of vision, the observers were instructed to select a position to avoid gloss perceived directly from the tooth or standard surface. Concerning the viewing time, it was recommended to focus on the tooth for a few successive seconds only, relieved each time by averting the eyes for a short period.

By varying the distance between the perforated grey shield and the tooth surface, it was possible to investigate 2 distinct situations, method 1 and method 2.

Method 1

The perforated shield was held parallel at a 30 mm distance to the tooth surface (figure 1) by use of a specially designed holder. The tooth crown was completely illuminated by ambient light through the open space.

The color of 10 teeth was determined twice by 25 observers. The time interval between the color determinations was about 1 week. The inter and intra-examiner reliability was assessed separately for the 3 visual color dimensions.

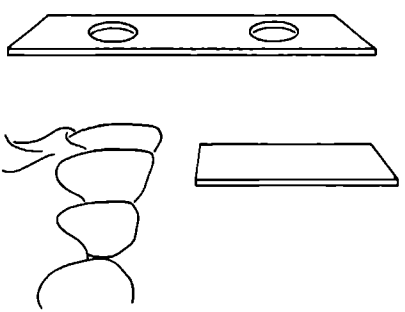

FIGURE 1:
Method 1; The perforated shield was held parallel to the tooth surface at a 30 mm distance.

Method 2

The perforated shield was kept tightly against the tooth surface (figure 2). The tooth crown was illuminated partly through the 4 mm diameter window, whereas the reflected light was collected at the same window.

To assess the difference between both methods, 8 examiners determined the color of 14 teeth using method 1 and method 2, respectively.

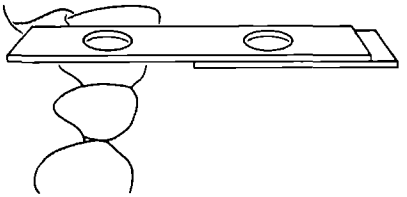

FIGURE 2:
Method 2; the perforated shield was kept tightly against the tooth.

I.3.4. RESULTS

Method 1

After a single explanation of the Hue, Value, and Chroma system of color ordering, all observers were capable of matching the color of teeth systematically using the set of color standards.
Often observers reported that the color of a tooth was situated between 2 adjacent standards. In these cases, they were permitted to define an additional intermediate color on a three-point scale between standards. The associated L*u*v* specifications were calculated by means of linear interpolation.

In table 1, the results are given for the analysis of variance for Hue, Value, and Chroma, respectively. The source of variation 'between observations' was found to be significant and has to be explained by differences between observers for all 3 color dimensions. There were no significant differences within observers. The differences between observers, however, contributed only to a very small extent to the total variance as compared with the highly significant differences between teeth.

For the examiners with the highest and the lowest Hue, Value, and Chroma scores, their average scores over 20 color examinations (1st and 2nd examination of 10 teeth) are given in table 2. When the differences between the lowest and the highest scores, are compared with the size of the color intervals between individual standards (0.1 for Hue, 5.0 for Value, and 0.12 for Chroma), these differences are still within the error of the method.

Equal results were obtained when the color of the reverse side of the perforated shield, the side turned towards the tooth, was black or white.

TABEL 2:
Average Hue, Value, and Chroma scores (± standard deviation) of the examiners with the highest and lowest scores respectively, for ten teeth assessed 2 times.

	Highest score (n = 2 x 10)	Lowest score (n = 2 x 10)
HUE	1.05 ± 0.01	1.01 ± 0.01
VALUE	73.1 ± 1.6	70.1 ± 0.4
CHROMA	0.50 ± 0.01	0.45 ± 0.02

TABLE 1:
Analysis of variance for the Hue, Value, and Chroma scores of ten teeth assessed twice by 25 observers.

Source of variation	DF	HUE		VALUE		CHROMA	
		MS	F	MS	F	MS	F
Between teeth	9	0.445	855.31***	2138.320	402.24***	0.729	513.46***
Between observations	49	0.001	1.50*	12.798	2.41**	0.003	2.18***
Between observers	24	0.001	2.10***	15.976	3.01***	0.004	3.13***
Within observers	1	0.000	0.00	1.364	0.25	0.001	0.43
Interaction	24	0.001	0.96	10.095	1.90**	0.002	1.30
Remainder	441	0.001		5.316		0.002	
Total	499						

Degrees of freedom (DF), mean squares (MS), and F-ratio's are given as well as the level of significance (*$p < 0.1$; **$p < 0.01$; ***$p < 0.001$).

Method 2

Observers expressed difficulty in obtaining a match using method 2. They also often expressed their surprise that the standards selected did not concur with their visual impressions of the tooth color.

The mean scores for Hue, Value, and Chroma with associated standard deviations, are presented for both methods in figures 3, 4, and 5, respectively. Figure 3 illustrates that the Hue-scores from the same teeth obtained using method 2 appeared more red than did those with method 1. Figure 4 demonstrates that, using method 2, the Value-scores were always found to relate to darker colors than those with method 1. Concerning the Chroma-scores, it can be concluded from figure 5 that the color from each tooth seems less intense with method 2 as compared with method 1. For each tooth, the direction of the color shift between methods 1 and 2 was consistent in each of the 3 color dimensions, whereas the magnitude of the color shift was variable for individual teeth (figures 3-5). For all color-scores, the standard deviations of the mean values were about 3 times larger for method 2 than for method 1.

I.3.5. DISCUSSION

Optimal circumstances were created for matching the color of teeth to opaque color standards using both methods. Daylight fluorescent tubes were selected for illumination because of their constant character and excellent reproduction of colors. Natural daylight was not used, since it is blueish and rather variable. A middle-high lighting intensity of 1500 Lux was chosen for evaluating the tooth colors. The ability to determine tooth colors does not differ significantly for a rather wide range of lighting intensities, provided the level of illumination is not extremely low or bright (Barna 1981). The color of each tooth was evaluated in the same environment, since the tooth color perceived is influenced indirectly by light reflected from surrounding colored objects. The tooth and the color standard were examined against an equal background by using a perforated grey shield. Color interpretation depends highly on the background to which the object is observed, due to physical processes in the retina. Furthermore, the large assortment of logically arranged color standards facilitated examiners in making a deliberate choice.

It appeared that, for the same tooth, very different color standards were selected whether method 1 or method 2 was used. The standards found with method 2, were always darker, more red, and less intense than those with method 1. This can be explained as follows: Principally, a tooth crown is to be considered as a double layered structure. The enamel, the surface layer, is a translucent and fairly colorless material. The inner layer is the more opaque and intensely colored dentin. Incident light is transmitted and scattered in the enamel layer. As a result of scattering in translucent material, incident light often leaves at the same surface as it entered the material, but at a different place. This phenomenon is referred to as volume reflection (CIE 1977). The average distance light traverses in a material, depends on the absorption and scattering coefficients of the material, depending in their turn on the wavelength of the light. In translucent objects, this average distance is of the order of mm's; in opaque material it is small compared with visually distinguishable distances. When gloss is avoided, the majority of light reflected from translucent objects, is due to volume reflection. The large average distance light traverses in translucent material, disturbs its color determination, unless lighting and viewing conditions are properly adapted.

In method 1, the tooth crown is illuminated completely by ambient light. The light reflected from the tooth surface, is observed through a 4 mm diameter hole. This situation is to be considered as large window illumination and small window collection. This construction provides proper inclusion of internal diffusion of light in the tooth and thus yields a proper value of volume reflection.

In method 2, the same window is used for illumination and observation of the reflected light. In such situations, a proper value of volume reflection is only obtained if the window diameter is large compared to the average distance light traverses in the material in the course of the internal diffusion. Considering this average distance in enamel, the size of tooth crowns is too limited to cover the desired diameter. Therefore, visual and instrumental color determinations on teeth that use the same window of illumination and observation, are inevitably subject to large

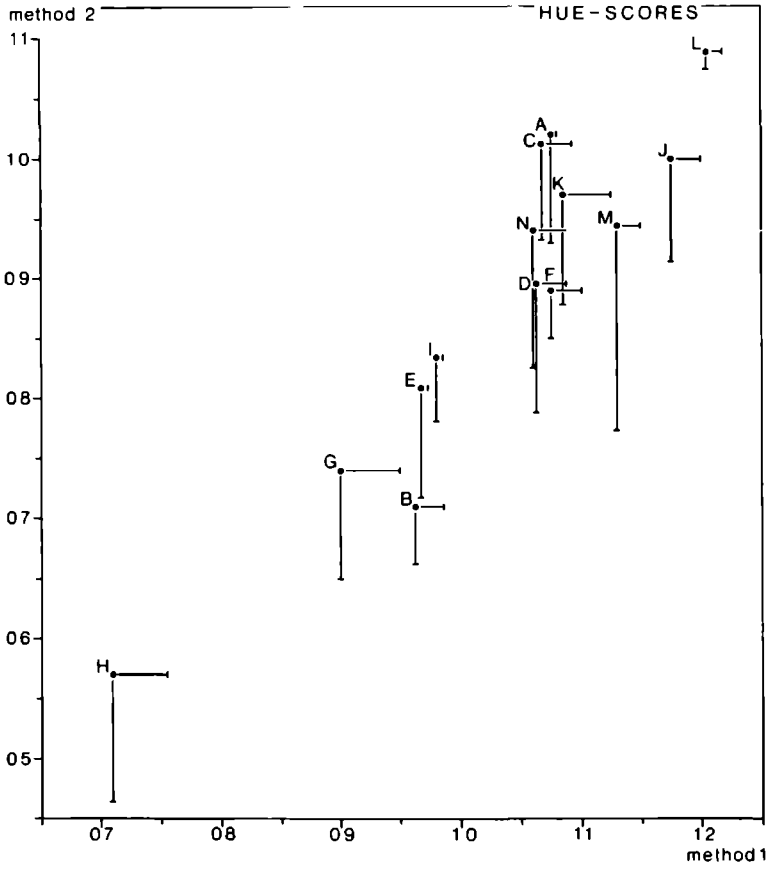

FIGURE 3:
Mean Hue-scores of 8 examiners using method 1 and method 2 for determining the color of 14 teeth (A-N). The lower the Hue-score, the more red the tooth color; the higher, the more yellow.
——| represents half of the standard deviation ($\sigma/_2$): in the vertical direction for method 2 and in the horizontal direction for method 1.

errors. This finding is essential since the lighting conditions in most instruments used for tooth color determination, resemble the situation in method 2. The color information obtained, will then be poorly related to the tooth color as it is observed in clinical situations, where the full tooth is illuminated.

The inter-examiner agreement for method 2, was lower than that for method 1 as expressed by the standard deviations of the mean values for Hue, Value, and Chroma, being 3 times higher in method 2 as compared to method 1. This can be explained from the same theory. In method 2, the shield is kept tightly against the tooth surface; thus, there is a boundary of the illumination. Because of the rather large diffusion of light in the enamel, this boudary of illumination causes a boundary effect within the area of observation. Presumably, this effect is weighed differently by different observers, leading to large inter-observer variations. In method 1, the

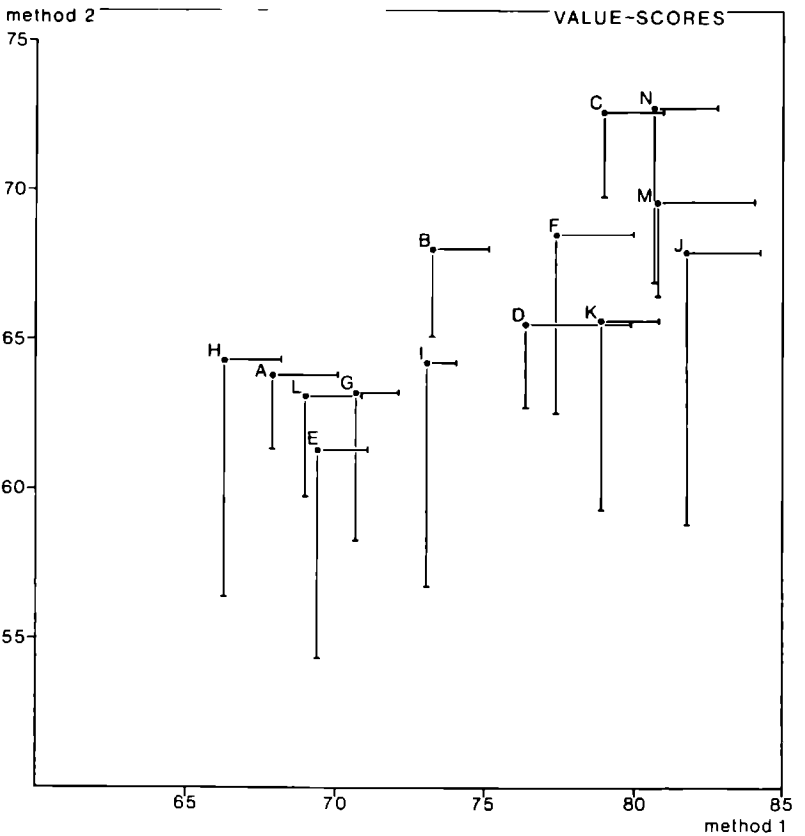

FIGURE 4:
Mean Value-scores from 8 examiners using method 1 and method 2 for determining the color of 14 teeth (A-N). The lower the Value-score, the darker the color of the tooth.
——| represents half of the standard deviation ($\sigma/_2$): in the vertical direction for method 2 and in the horizontal direction for method 1.

full tooth is illuminated, and boundary effects do not occur. We conclude that method 1 is strongly to be preferred over method 2.

In method 1, several important factors concerning visual tooth color determination are combined. A wide range of logically arranged color standards is available. Due to spectrophotometric analysis of the standards, the tooth colors visually obtained with method 1, can be expressed in CIE color specifications. The procedure of color determination is standarized and based on the optical phenomena occurring in teeth. The reproducability of the method is proven.

For some teeth, a perfect color match could not be obtained using method 1, unless the set of color standards was enlarged with some intermediate color standards. This may explain the slight differences in color matching reproducibility between individual teeth. For further improvement, it is suggested that the standard color collection should be extended.

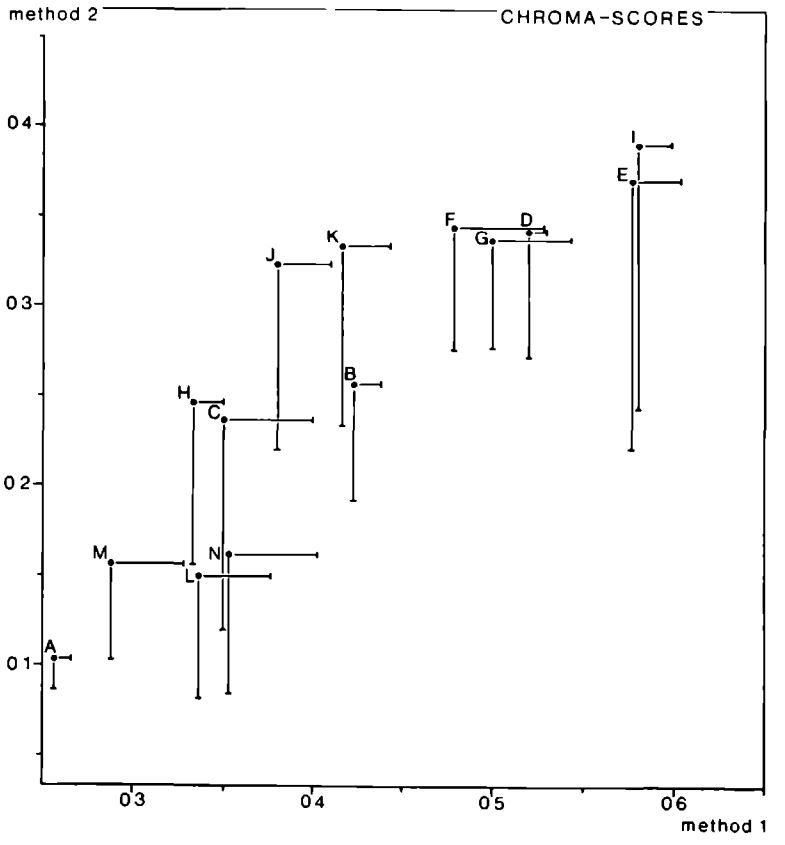

FIGURE 5:
Mean Chroma-scores of 8 examiners using method 1 and method 2 for determining the color of 14 teeth (A-N). The lower the Chroma-score, the less intens the tooth color.
——| represents half of the standard deviation ($\sigma/_2$): in the vertical direction for method 2 and in the horizontal direction for method 1.

For proper use of method 1, several conditions should be fulfilled. The translucency of dental enamel decreases drastically on dehydration, resulting in a dull white appearence of the tooth, whereas the color of the underlaying dentine becomes undetectable (ten Bosch 1979). Therefore, the moisture content in the teeth to be examined should be controlled. Desiccation of the enamel was prevented by continuous storage of the tooth in water, except for the short periods of color evaluation. Further conditions concern the illumination of the samples. Gloss from the tooth or standard surface should be avoided, since gloss provides only information about the light source. In this context, it is also important to ascertain that no shadow is created on the tooth or standard surface. For method 1, a suitable distance between the tooth and the perforated shield was assessed experimentally as 30 mm.

Method 1 can be applied clinically to determine the color of anterior teeth. The method is a suitable research aid to assess color changes in longitudinal clinical studies on internal and external tooth discoloration. Usually, the amount of discoloration in such studies is estimated visually according to arbitrary scales, consisting of 3 to 5 criteria (Schemehorn 1982). Recently, the staining potential of a number of dental materials was established using method 1 (chapters II.4 and II.5.). Method 1 can possibly also be used to evaluate, intra-orally, the color stability of dental materials. Furthermore, the principles used in method 1, served as a basis for the development and calibration of a new colorimeter for intra-oral tooth color determination (chapter I.4.). Ultimately, use of this method will give guidance for the improvement of the color matching required for the manufacture of artificial teeth.

A COMPARISON OF NEW AND CONVENTIONAL METHODS FOR TOOTH COLOR QUANTIFICATION[1]

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I.4.1. INTRODUCTION

A reliable method for intra-oral tooth color quantification, would be valuable for prosthetic purposes as well as for clinical studies on tooth discoloration. A number of criteria could be defined for a proper method to determine the color of teeth (chapter I.1.). The method should be based on the optical properties of teeth in order to obtain clinically relevant and generalizable information. The method should be reproducible, sensitive, and simple to use. The measurements should possibly be performed intra-orally and they should be non-destructive. The data obtained should be expressed in CIE color specifications.

The methods available to evaluate the color of tooth crowns, can be divided into 2 main categories: visual and instrumental. The first category employs visual comparison with color standards; the second is characterized by the use of optical instruments. The visual color matching procedure concurs best with the original definiton of color, which is based on visual field comparison (CIE 1970).

Visual tooth color determination by comparison of the tooth with color standards, is most frequently applied in dentistry. The tooth and the standard are observed simultaneously under the same lighting conditons. Prosthetic shade guides commonly serve as color standard to which the color of a tooth is matched. Nevertheless, several disadvantages of these shade guides could be mentioned. The range of available shades is inadequate and the shades are not logically distributed (Sproull 1973). It is not possible to translate the results obtained into CIE color specifications. There is a lack of consistency among and within individual dentists in matching tooth colors using the shade guides (Cullpepper 1970; Barna 1981; O'Neal 1984). This disagreement is probably due to the fact that matching tooth colors to prosthetic shade guides is a multifactorial process. The process includes color, shape, structure, gloss, and dissimilarities between the centre and the sides of a tooth. Different observers may weigh the effects of these factors differently.

To overcome these problems, an alternative method for visual tooth color determination was developed (chapter I.3.). A large collection of logically arranged color standards was introduced. The CIE color coordinates of the standards were established. The mid-cervical part of the labial tooth surface and the standard were viewed through 2 small holes in a neutral grey shield. Using such a perforated shield, one factor was isolated: the color of the body of the tooth. All other factors that influence the process of comparison, were thereby eliminated. Based on theoretical considerations on translucency and observers practical experience, it was concluded that the shield should be held at a distance from the tooth and the standard. In view of the CIE definition of color, it is clear that the method is pre-eminently suitable for tooth color quantification.

Instrumental color measurement could be preferred over visual color determination, because instrumental readings are objective and more

[1]To be submitted to J Prosthet Dent

rapid. Several attempts have been made to establish the color of teeth by adapting conventional optical instruments to the limited size of tooth crowns (Ishikawa 1969; Sproull 1973; Grajower 1976; McEntee 1981). The diameter of the window for illumination and collection of the reflected light, is mostly drastically reduced. The regions of the color space in which the tooth colors were found, however, differed significantly between various investigators (McEntee 1981). The Chromascan (Sterngold, Stamford, USA) is a colorimeter, especially designed to assess the color of teeth (Exposite 1977). In this paper, another colorimeter for tooth color measurement is described. This instrument is referred to as the fiber-colorimeter.

In the present study, the following instruments for tooth color quantification are compared with the visual method described in chapter I.3.: the fiber-colorimeter, a conventional spectrophotometer, and the Chromascan.

I.4.2. MATERIALS AND METHODS

Samples

Twenty-two humidity controlled, extracted human upper incisors were used. The teeth were selected visually to cover a wide range of natural tooth colors. To prevent discoloration of the tooth crowns during the study, the external tooth surfaces were mechanically cleaned, the pulps were extirpated and the pulp cavities instrumented. In additon, 16 acrylic resin incisors (Ivoclar, Schaan, Lichtenstein) were used.

The color of the mid-cervical part of the labial tooth surfaces was evaluated using four different methods refered to as method 1 to 4. During the color determinations with methods 1, 2, and 3, the teeth were placed ,in between adjacent teeth, in the dental arch of a phantom head. For method 4, the teeth were analyzed seperately within the instrument. During the entire experimental procedure, desiccation of the natural teeth was avoided by continuous storage in water.

Color scales

All data were expressed in terms of Hue, Value, and Chroma. Hue is shade or color tone e.g. red, blue, green, etc. Value is the degree of grey or brightness. The term Chroma indicates saturation (Munsell 1961). The XYZ color specifications resulting from method 1, 2, and 4, were converted to Hue, Value and, Chroma as defined and recommended by CIE (1976). The Chromascan data (method 3) were translated to Hue, Value, and Chroma as defined by the manufacturer.

Method 1: Matching with color standards

This method, which is described in chapter I.3., is abbreviated as the 'standards method'. The standards were opaque glossy cardboards (22 x 40 mm), logically arranged according to Hue, Value, and Chroma (Sikkens Color Collection 20/21, Sikkens, Sassenheim, The Netherlands). The CIE color specifications XYZ of the standards were computed from their individual reflection curves (RFC-3 spectrophotometer, Zeiss, Oberkochen, BDR) for 2^{o} observation and lightsource D_{65}. In the set of standards, 7 approximately equidistant Hue steps, 8 Value, and 6 Chroma steps could be distinguished at intervals of 0.1, 5.0, and 0.12, respectively.

The teeth were illuminated by daylight fluorescent tubes (TL-47, Phillips, Eindhoven, The Netherlands), the lighting intensity was 1500 Lux. Background and environment were standardized and of neutral colors.

The standards were held adjacent to the tooth surfaces in the same

horizontal plane. Both surfaces were viewed simultaneously through 2 holes (diameter 4 mm; 6 mm apart) in a neutral grey shield (15 x 35 mm). The shield was kept parallel to the tooth surface at a distance of 30 mm. The samples were illuminated by ambient light through the open space. Gloss perceived directly from the tooth or sample surface was avoided.

The observers selected the best match from the set of color standards or indicated on a three-points scale the best match between standards. The associated color specifications were calculated by means of linear interpolation.

Method 2: Fiber-colorimeter

In this method, a double box (20 x 20 x 10) was employed to illuminate the tooth and a white reference surface, respectively (figure 1). In the front panel of each part of the box, was an observation hole (diameter 4 mm). The inside of the box was white, except for a black ring-shaped gloss-trap (outer diameter 8 mm) around the observation holes. Each part of the box was illuminated with illuminant C light through a fiber. A diffusor in both parts ensured a rather diffuse and symmetric situation of illumination. The fibers, which were made on special order, were compensated for spectral dependence of light losses (Tintometer, Salesbury, UK).

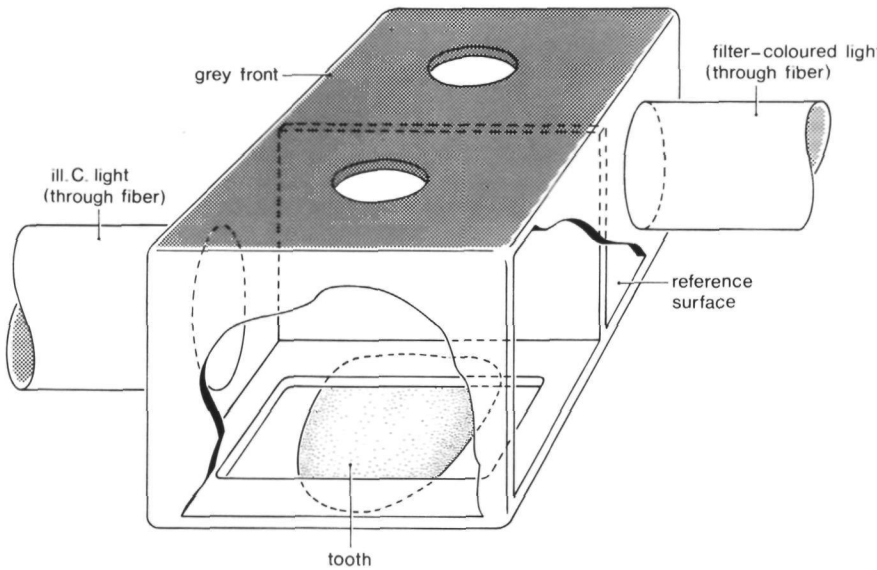

FIGURE 1:
Schematic representation of the double box of the fiber-colorimeter. The tooth is illuminated in one box with ill. C light of variable intensity. The back panel of the adjacent box, the reference surface, is illuminated with colored light from the same source but passing a set of subtractive filters.

One part of the box, having no back panel, was placed against the teeth. The light intensity in this part was adjustable by means of a diaphragm system in the lamp house, to which the fiber was connected. The white back panel of the other part of the box, served as reference surface. It was illuminated by light from the same source that had passed a set of

subtractive red, yellow, and blue filters (Tintometer, Salesbury, UK). Outside the box, the observer views the tooth and the reference surface simultaneously through 2 holes in the neutral grey front panel.

The colors of both surfaces were matched by adjusting the colors of red and yellow filters at the reference site and the intensity of the white light on the tooth surface. The color of the blue filter was kept constant.

The diaphragm setting of the fiber-colorimeter was calibrated by measuring Munsell color standards (Munsell Color, Baltimore, USA). The CIE color coordinates XYZ of these standards were known from measurements made with the same spectrophotometer as used in method 1. Using a computer program, provisional XYZ color specifications of the samples were computed for lightsource C, based on the positions of the filters (Hunter 1975). For this calculation, the absorption spectra of the filters were used, which were provided by their manufacturer. The diaphragm setting was not included in this calculation; the diaphragm highly influences the Y coordinate. Then, the diaphragm settings were related to the known CIE data for Y of the Munsell standards. This relation turned out to be exponential, it was used to calibrate the diaphragm settings. After this calibration, the XYZ color specifications of each tooth were calculated from the filter and diaphragm positions obtained in the measurements.

Observation

The color evaluations in methods 1 and 2 were performed by 2 trained observers, whose color vision was tested to be good (100 Hue Farnsworth-Munsell test). They were dressed in a white coat and observed the samples at a convenient distance of about 25 cm. The color of each tooth was determined independently by the 2 observers. In case of disagreement the color was re-assessed.

Method 3: Chromascan

After a 10 minutes warming-up period, the Chromascan was calibrated using the white button, according to the manufacturer's instruction. The probe tip was placed on the teeth, perpendicular to the labial surfaces. Between the probe and the teeth a special liquid was applied (Chroma-coupler, Sterngold, Stamford, USA). The color of each tooth was measured 10 times and the average RGB values (Red, Green, and Blue) were calculated.

Method 4: Spectrophotometer

The teeth were analyzed using a spectrophotometer (RFC-3, Zeiss, Oberkochen, BRD) with a window diameter of 5 mm. The instrument was calibrated on a black and a white standard. The tooth crowns were fixed against the window using wax (Imprint correction wax, Hawe-Neos Dental, Lugano, Switzerland). The gloss-trap of the apparatus was used. From the reflection spectra obtained, the XYZ tristimulus values were calculated for 2^{o} observation and for standard lightsource D_{65} (Driscoll 1978; Billmeyer 1981). Each tooth was analyzed twice and the mean XYZ Values were computed.

I.4.3. RESULTS

The Hue, Value, and Chroma-scores, obtained from 22 natural and 16 artificial teeth using four different methods for tooth color determination, are presented in figures 2, 3, and 4, respectively. The relations between the standards method (method 1) and 3 distinct instrumental methods (methods 2-4), is demonstrated in linear regression lines and correlation coefficients. In figures 2 to 4, natural teeth are indicated by

full symbols whereas open symbols refer to artificial teeth.

The observers reported that the fiber-colorimeter was simple to handle, although considerable training was required to learn which filter setting change was needed to obtain a desired color change of the reference field.

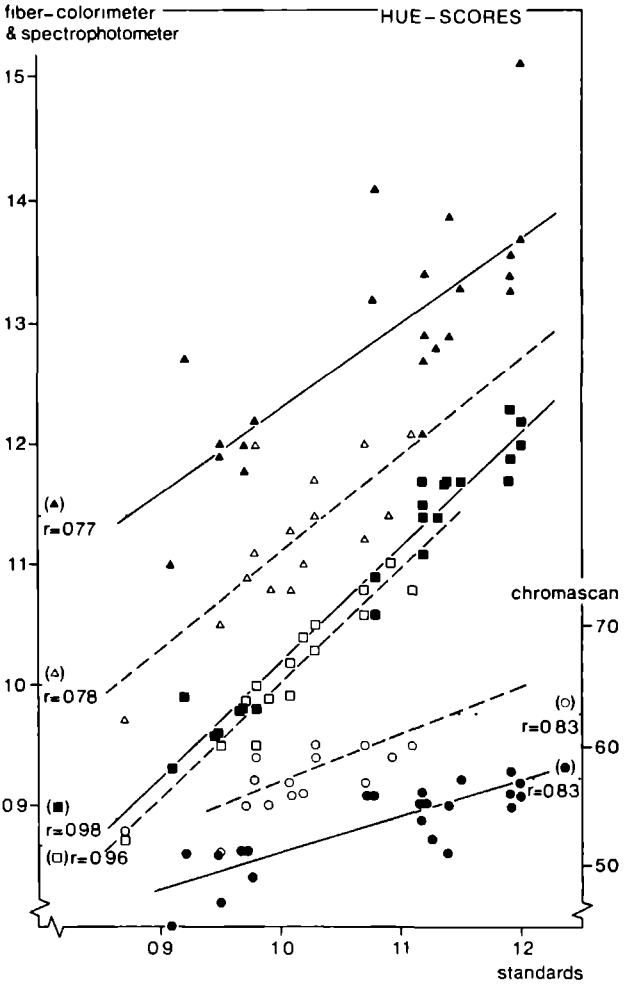

FIGURE 2:
Comparison of Hue-scores of 22 natural teeth (full symbols) and 16 artificial teeth (open symbols). The score obtained with the standards method is on the abscina. The scales for Hue-score, determined with the fiber-colorimeter (■ , □) and the spectrophotometer (▲ , △), are the same as shown on the left ordinate. The Hue-score of the Chromascan (● , ○) is on a different, not related scale as shown on the right ordinate. Straight lines indicate lines of linear regression; full lines for natural teeth, interrupted lines for artificial teeth. Correlation coefficients are also given.

I.4.4. DISCUSSION

In analyzing tooth colors, the prime concern is that the results obtained are clinically relevant. Therefore, it is essential that the measuring procedure is based on the optical properties of dental tissue. Principally, a tooth crown is to be considered as a double layered structure. The enamel, the superficial layer, is a translucent and fairly colorless material. The inner layer is the more opaque and more intensely

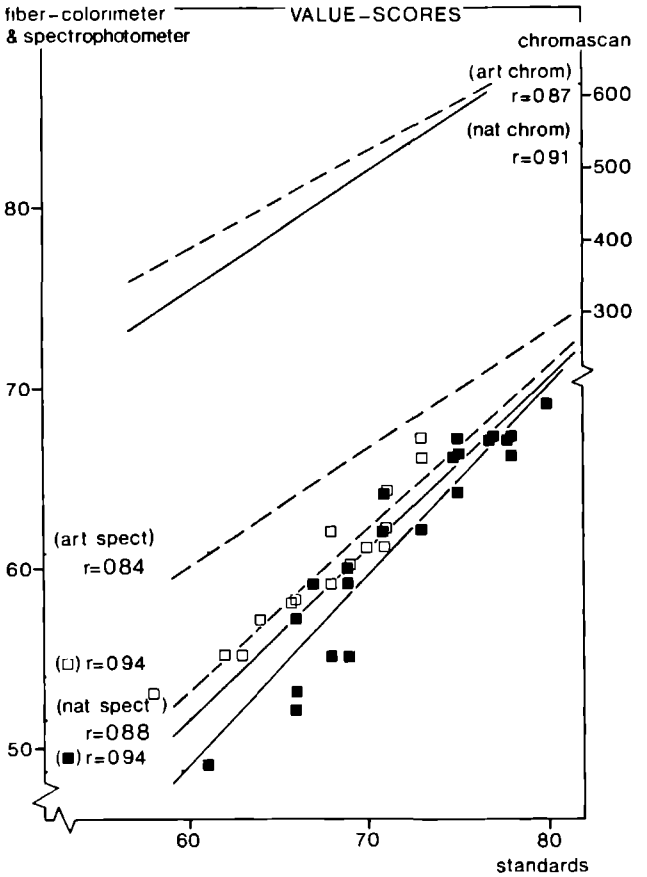

FIGURE 3:
Comparison of Value-scores of 22 natural teeth (full symbols) and 16 artificial teeth (open symbols). The score obtained with the standards method is on the abscina. The scales for Value-score, determined with the fiber-colorimeter (■ , □) and the spectrophotometer, are the same as shown on the left ordinate. The Value-score of the Chromascan is on a different, not related scale as shown on the right ordinate. For the spectrophotometer and the Chromascan the points are omitted. Straight lines indicate lines of linear regression; full lines for natural teeth, interrupted lines for artificial teeth. Correlation coefficients are also given.

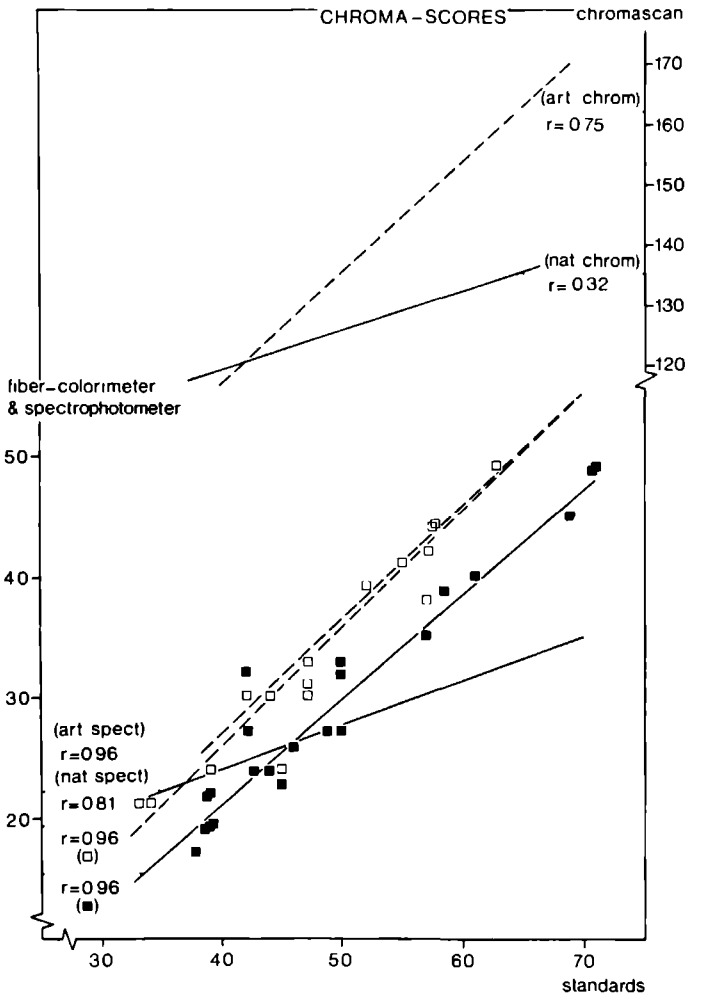

FIGURE 4:
Comparison of Chroma-scores of 22 natural teeth (full symbols) and 16 artificial teeth (open symbols). The score obtained with the standards method is on the abscina. The scales for Chroma-score, determined with the fiber-colorimeter (■, □) and the spectrophotometer, are the same as shown on the left ordinate. The Chroma-score of the Chromascan is on a different, not related scale as shown on the right ordinate. For the spectrophotometer and the Chromascan the points are omitted. Straight lines indicate lines of linear regression; full lines for natural teeth, interrupted lines for artificial teeth. Correlation coefficients are also given.

colored dentin. Incident light is transmitted and scattered in the enamel layer. As a result of scattering, incident light enters and leaves the tooth through the illuminated labial surface but at a different place. This phenomenon is referred to as volume reflection (CIE 1977).

When gloss is avoided, usually the majority of light reflected from objects, is due to volume reflection. The average distance light traverses in a material, is related to the absorption and scattering coefficients of the material, depending in their turn on the wavelength of the light. In translucent materials, this average distance is of the order of mm's; in opaque materials, it is small compared to visually distinguishable distances. The large average distance light traverses in translucent materials, interferes with its color determination (ten Bosch 1985). In particular, color readings on small translucent objects will be disturbed, unless lighting and viewing conditions are properly adapted.

Commonly, an object is analyzed with the same window of illumination and collection of the reflected light. Entering light may be volume-reflected so far inside a material, that it emerges beyond the boundary of the window and thus becomes excluded from the measurement. This is called edge-loss and is related to the average sideward displacement of light inside a material. For a proper color determination, these light losses have to be negligable. Therefore, the window diameter should be large compared to the sideward displacement of the light.

Considered the average distance light traverses in enamel, the size of the tooth crown is too limited to cover the desired diameter. Color determinations on teeth using the same small window for illumination and observation, therefore, are inevitably subject to large errors. Problems of this nature are mentioned before by Hunter (1975) and Cook (1985). Furthermore, McEntee (1981) suggested that insufficient color information from dentin is obtained by small window reflectivity measurements on teeth. To overcome these problems, a visual method for matching tooth colors with color standards was developed, based on the optical properties of dental enamel (chapter I.3.).

The lighting geometry in the fiber-colorimeter (method 2) and the standards method (method 1) is similar. Using method 1 and method 2, highly correlated results were obtained from natural and artifical teeth (figures 2-4). Minor variations are probably induced by the subjectivity of the color matching procedures in both methods. The fact that the teeth were observed under slightly different light sources (method 1: ill. D_{65}; method 2: ill. C), will also play a role. For Hue, Value, and Chroma, the regression line of the scatter plot may well be approximated by a straight line under 45^{o} (figures 2, 3, and 4, respectively). Equal Hue-scores were obtained with method 1 and 2. The Value and Chroma-scores found with method 2, however, were consistently too low. The lower Value-scores could be caused by light escaping between the tooth edge and the box wall. Since all teeth were analyzed in a standardized environment, this loss of light was about the same for each tooth. A decrease in Chroma-score is to be considered as the admixture of white light. This light could possibly originate from specular reflection perceived from the tooth surfaces. In that case, the gloss-trap in the illuminating box was inadequate, which is well plausible. Different reductions in Chroma were observed for natural and artificial teeth, which could result from the difference in refractive index of water (1,5: wet surface natural teeth) and plastic (1.3: acrylic resin teeth). Neither light loss aside teeth, nor specular reflection is likely to interfere with the Hue-score. To improve the Value and Chroma results, obtained with the fiber-colorimeter, revision of the illuminating box is required. Furthermore, extensive training is necessary for

handling the instrument. In future, therefore, attempts should be made to replace the visual color matching procedure by photo-electric detection using a similar geometry of illumination and collection.

From an optical point of view, the lighting situation in the Chromascan (method 3) seems to be quite acceptable. Using the Chromascan, the whole tooth crown is illuminated and the reflected light is collected through a 2 mm probe tip. Nevertheless, the Hue and Value-scores of method 1 and 3 only showed some correlation, whereas the Chroma-scores were poorly related. Perhaps the prime cause of the disagreement was the manufacturer's use of an aberrant scale of Hue, Value, and Chroma. The exact relation between Chromascan data and CIE color specifications is still unclear (Bangston 1982). Because the absolute color-scores obtained with method 1 and 3 are incomparable, a meaningful discussion of the results is not possible. The Chromascan has some additonal limitations. The calibration procedure has to be repeated frequently during a series of measurements. Moreover, the instrument is no longer being produced.

The spectrophotometric data (method 4) and the data with the standards method (method 1) were rather different for natural teeth. The discrepancy could be explained by the fact that in method 4 the same small window was used for illumination and collection of the reflected light. As a result of edge-losses through the translucent enamel, the color determinations were disturbed. Since a spectrophotometer detects all light reflected from the full window (the fiber-colorimeter only measures light from the centre), windows larger than 5 mm, which might give less side-loss, were not permissible. Edge-loss affects the Hue, Value, as well as the Chroma-scores (chapters I.2. and I.3.), which is demonstrated in figures 2, 3, and 4, respectively. The effect of edge-loss depends on the thickness and mineralization of the enamel layer of individual teeth, which possibly contributed to the variation observed between method 1 and 4. For artificial teeth, smaller differences were found between method 1 and 4. Since artificial teeth are more opaque than natural teeth, probably the effect of edge-loss is less important. Finally, the gloss-trap in a spectrophotometer is made for flat samples. Because teeth have curved surfaces, the Chroma-scores might be too low due to specular reflection.

I.4.5. CONCLUSIONS

1. When conventional optical instruments are adapted to color measurements on tooth crowns by reducing the window diameter, the color determinations will be subject to large errors.

2. Based on the results from this study, the Chromascan appears to be unsuitable for tooth color measurements.

3. The fiber-colorimeter is a promising instrument for tooth color quantification, although extensive technical improvement is necessary.

DISCUSSION AND CONCLUSIONS

I.5.1. DISCUSSION

In the previous chapters, 2 methods for tooth color determination are introduced. The first method, the so-called 'standards method', is based on visual comparison with color standards (chapter I.3.). For the second method, referred to as the 'fiber-colorimeter', a conventional colorimeter is modified for tooth color measurements (chapter I.4.).

With restriction perhaps of the time factor, the standards method meets all criteria defined for proper tooth color determination as outlined in paragraph I.1.5. The standards method is based on the optical properties of teeth, which garantees that the color information obtained is clinically relevant. The method is non-destructive and can be applied for intra-oral use. Reproducible results are obtained using the method, in addition the data are expressed in CIE color specifications.The sensitivity for color differences was sufficient within the range of natural tooth colors. For experienced observers, an accurate color determination takes about half a minute.

The scientific significance of the standards method for tooth color determination, lies in the clinical validity of the data. In chapters I.1. and I.2., the optical processes occurring in translucent materials, such as dental enamel, were scrutinized. In designing a method to analyze tooth color, efforts were made to adapt the lighting and viewing conditions to the optical properties of enamel (chapter I.3.). This ensured the diffusion of light in the tooth to be properly included in the measurements, which is essential for the concurrence with traditional clinical observation. The color information obtained with the standards method, seems to correspond to the tooth color as it is observed in clinical situations, where the full tooth crown is illuminated.

The idea for the development of the fiber-colorimeter (chapter I.4.), arose from the succesful results obtained with the standards method. The gradation of the color scale is about 5 times more refined for the fiber-colorimeter than for the standards method. The fiber-colorimeter appeared to be a promising instrument for tooth color measurements, although technical improvement is necessary. Basically, the colorimeter is simple to handle, however, extensive training is required to learn which filter setting corresponds to the desired color of the reference surface. In future, the human observer in the colorimeter can perhaps be replaced by a photo-electric detector, which will reduce the required operator time.

A reliable method for intra-oral tooth color determination will be useful in numerous research projects in dentistry. The standards method can be applied for clinical or laboratory studies on extrinsic as well as intrinsic tooth discoloration. In previous discoloration studies, the color changes were scored according to arbitrar scales limited to 3 to 5 criteria (Schemehorn 1982). Our more advanced method for tooth color quantification, will facilitate more detailed research on this topic. Many investigations could be proposed regarding the etiology of tooth discoloration. Exogeneous factors causing extrinsic tooth discoloration could be studied such as the use of chlorhexidine and stannous fluoride applications, the consumption of food, the smoking of tobacco, the chromatogenic bacteria in plaque, etc. Concerning intrinsic discolorations, the staining potentials of the following dental materials could be investigated: temporary and permanent filling materials, endodontic drugs and sealers, materials used as a base or cavity liner, materials used for cementation, etc. In addition, the method can be employed to establish the

effectivity of preventive treatments or techniques to destain discolored tooth. The long-term color stability of dental restorations in the mouth, can be assessed by standards method as well. This will enable the extension of previous laboratory studies on color stability into the clinic. In these laboratory studies, conventional spectrophotometers were adequate because large samples were available (Dennison 1978).

The standards method can also be used for prosthetic purposes. First, the method will be helpful in composing prosthetic shade guides based on scientific rather than emperical grounds. The range of available shades in prosthetic shade guides, is often subject of discussion, as is the distribution of the shades (Sproull 1973). The region of natural tooth colors, could be established in an epidemiological experiment using the standards method. The information acquired from such study, could be used for reconsiding the adequacy of the current shade guides. Second, the results obtained with the standards method, will give guidance for the color matching procedure using prosthetic shade guides. In dental practice, routine tooth color determinations are performed by visual comparison with the reference teeth from prosthetic shade guides. The reference tooth is kept adjacent to the tooth to be matched. A lack of consistency is reported among and within individual dentists in performing such matches (Cullpepper 1970; Barna 1981; O'Neal 1984). This is not surprising because matching is a multifactorial process including: surface character, structure in the tooth, incisal color, shape, gloss, size, etc. We intended to isolate one factor ,the color of the body of the tooth, and quantify that properly. In the visual method, recently developed for tooth color quantification, the tooth and the standard are viewed simultaneously through a perforated grey shield (chapter I.3.). This procedure has been shown to be essential to obtain reliable results. The use of the perforated shield, probably results in a separation of crown color from the other factors. For improving the process of color matching with prosthetic shade guides, therefore, is suggested to employ a similar shield. Third, the standards method allows for standardized comparisons because tooth colors are expressed in CIE color specifications. Further research should be undertaken to translate the CIE data obtained from a natural tooth, into a recipe for the manufacture of the matching artificial tooth.

The color of the gingiva is important as parameter for the stage of gingivitis (Carranza 1984). In determining the color of teeth and gingival tissues, the same problems are involved (ten Bosch 1985). In periodontics, therefore, the standards method might serve as a basis to develop a technique for color measurements on the gingiva.

The standards method might be suitable to detect caries risk-groups in a population. Persons having white teeth, are asserted to be more susceptable for caries than persons with a dark yellowish tooth color. This traditional view yields perhaps a valuable criterium to predict a high risk for caries. A relation between tooth color and caries resistance, could theoretically be explained from the construction of the enamel layer. Well calcified, homogeneous enamel is translucent, as a result of which the intensely colored dentin is visible. Irregularly structured enamel, which is more liable to caries decay, scatters highly whereby the tooth has a more white appearance. To verify this theory, persons of a suitable age group should be examined on tooth color in relation to past caries experience. Using a Chromascan, no such relation could be demonstrated (Kerosuo 1982). However, the relevance of this study is doubtful since the Chromascan seems to be unsuitable for tooth color measurement (chapter I.4.).

I.5.2. CONCLUSIONS

1. The visual method for matching tooth colors with color standards, is pre-eminently suitable for tooth color determination. The method can be applied for numerous purposes.

2. The fiber-colorimeter seems to be a promising instrument for tooth color quantification, although extensive technical revision is necessary.

INTRODUCTION

The first step in investigating the staining potentials of endodontic materials, is to design a technique to induce controlled intrinsic tooth discoloration. Considering the lack of research data on this topic, was decided for an in-vitro approach. It seems reasonable to use extracted teeth for this purpose. Three factors should be taken into account in developing a useful technique for experimental tooth discoloration: (a) the clinical relevance of the technique, (b) the reproducibility of the discoloration, and (c) the humidity control of the teeth.

Ad a: During endodontic therapy, various materials are introduced through the access opening of a tooth. The staining components of the material, diffuse from the pulp cavity into the dentin causing intrinsic tooth discoloration (Vogel 1975). Efforts will be made to simulate this clinical situation in our experimental design. In addition, the technique should be suitable to investigate solid as well as liquid materials. Because the crown is the visible part of a tooth, coronal discoloration is clinically most relevant. For this reason, the intrinsic stains showing through the enamel have to be recorded.

Ad b: With respect to the selection and preparation of the teeth, attention has to be payed to the reproducibility of the discoloration process.

Ad c: The degree of light scattering in the enamel, drastically increases with dehydration, as a result of which the enamel becomes white and opaque (ten Bosch 1979). If enamel looses its translucency, the color of the underlaying dentin becomes invisible. In this context, it is important that discolorations after endodontic therapy probably become noticeable in course of time. Therefore, longitudinal in-vitro studies are necessary. To control the moisture content of the teeth during the entire experimental procedure, samples have to be incubated in a humid environment resembling the oral cavity.

The technique developed for creating experimental tooth discoloration, will be applied for investigations on the staining properties of endodontic drugs and filling materials. Eventually, the effectivity of internal bleaching to eliminate stains caused by endodontic materials, will be examined in-vitro.

LITERATURE SURVEY ON TOOTH DISCOLORATION

II.2.1. EXTRINSIC DISCOLORATIONS

Extrinsic tooth discoloration is characterized by accumulation of stain on the tooth surface (Spouge 1973). The majority of tooth discolorations seems to be of extrinsic nature (Vogel 1975). Extrinsic tooth discolorations are induced by exogenous pigments, which originate from outside the body. Extrinsic discolorations can be removed by mechanical means. Firmly attached stains require professional scaling and polishing, otherwise regular oral profylaxis will be sufficient. Improvement of oral hygiene and suspension of stain-promoting habits, will prevent recurrence of the discoloration (Eriksen 1978). Irregularities in the tooth surface and exposed roots increase the possibility for retention of discolored integuments.

The mechanisms involved in the development of extrinsic discoloration, can be devided into 3 main categories: chromatogenic bacteria, retention of colored substrates, and chemical transformation of pellicle components (Eriksen 1978).

Chromatogenic bacteria

Bacteriologic stains are related to specific ecological conditions in the oral flora. Yellow, green, and orange stains are caused by chromatogenic bacteria in plaque in connection with poor oral hygiene (Sutcliffe 1967). On the other hand, brown to black deposits of bacterial origin are usually seen in mouths with good oral hygiene (Theilade 1973).

Retention of colored substrates

The passage of colored substrates through the oral cavity, may lead to the retention of pigments in the plaque or pellicle. This type of discoloration may be observed after consumption of foods and beverages with strong coloring components (e.g. blueberries). Since such discolorations are mostly temporary, their importance is subject of discussion.

Chemical transformation of the pellicle

This group of discolorations appears mainly as a brown stain. Many promising antibacterial agents used for chemical plaque control, as chlorhexidine and stannous fluoride, induce marked extrinsic discolorations (Fløtra 1971; Svantum 1977). This unwanted side effect can be explained by the chemical transformation of pellicle components (Eriksen 1985). The formation of colored products from chemical transformation of pellicle components, is probably due to a combination of 3 factors: (a) the denaturation of pellicle proteins, (b) the interaction between the pellicle and reactants introduced in the oral cavity, and (c) the thickness of the pellicle (Eriksen 1978).

Ad a: Several detergents and organic acids have a strong denaturating effect on pellicle proteins. Tannic acid, a natural constituent of fruits, wines, coffee, and tea, provides the formation of a brown stained pellicle (Nordbø 1977). The strong discoloration related to the oral use of chlorhexidine, results partly from the detergent properties of the material. These properties allow for the formation of pigmented metal precipitates (Ellingsen 1982; Nordbø 1982).

Ad b: A variety of substances may react with pellicle components to form colored products. Other substances may catalyse browning reactions involving the pellicle. Aldehydes, occuring in baked products and fruits, are known to interact with pellicle proteins to form dark brown organic

complexes (Berk 1976). In addition, brown precipitates are mediated by cations like iron (oral treatment of anemia), tin (topical stannous fluoride application) and strontium (Mortimer 1971). The connection between smoking and tooth discoloration (Ness 1977) may partly be explained from this mechanism as well (Vogel 1975). The glycoproteins of the pellicle might serve as substrate for non-enzymatic reactions leading to the formation of brown pigmented products (Berk 1976). Chlorhexidine has been shown to catalyze such browning reactions (Nordbø 1979).

Ad c: The absence of plaque, induced by chemical plaque control, favors the formation of an extra-ordinary thick pellicle and thus the availability of substrate for staining reactions (Titanoff 1976).

Furthermore, it is demonstrated that constituents of food react with chlorhexidine to form colored products (Nordbø 1971; Addy 1979; Prayitno 1979). These products may in turn discolor tooth surfaces. According to Eriksen (1985), it is not likely that dietary factors play a decisive role.

II.2.2. INTRINSIC DISCOLORATIONS

Intrinsic discolorations are localised within the tooth structure (Spouge 1973). As opposed to extrinsic tooth discoloration, intrinsic discoloration results of either exogenous or endogenous pigments. The latter of these pigments is produced by the body itself. To improve the appearence of intrinsically stained front teeth, they are usually covered by a full crown, a laminar veneer (Faunce 1976) or a layer of composite (Jordan 1977). Sometimes, intrinsic discolorations can be succesfully destained by bleaching.

Intrinsic discoloration of the dentition may be caused during the stages of tooth formation, however, it may also occur after completion of the dentition.

Pre-eruptive discoloration

Hereditary defects usually involve the deciduous and permanent dentition. Dentinogenesis imperfecta is a developmental disturbance of the dentin and pulp. After eruption, the tooth color is normal, but later it becomes yellow or grey-brown (Witkop 1958; Pindborg 1983). Amelogenesis imperfecta is a hereditary structural anomaly affecting the enamel. Divers clinical manifestations are reported, varying from a chalky white to yellow, red or brown tooth discoloration (Darling 1956; Pindborg 1983). Following acid-etching of the enamel, stains from amelogenesis imperfecta respond well to bleaching with hydrogen-peroxide (Boksman 1983).

Congenital defects are known to cause intrinsic discolorations of the primary and secundary dentition during the formative phase (Pindborg 1970). Hemolytic diseases of the newborn, as erythroblastosis fetalis and icterus gravis neonatorum, may be associated with a yellow to green tooth discoloration. The color is due to bilirubin and biliverdin accumulation, which are decomposition products of blood pigments (Losch 1940; Spouge 1973). Several metabolic diseases, like porphyria and alkaptonuria, may include the complication of brownish stained teeth (Sidhu 1972; Link 1973). Other tooth discolorations due to bloodpigments, are observed in relation to neonatal hepatitis and congenital bileduct defect (Pindborg 1970).

Another cause of intrinsic tooth discoloration, is drug administration during the development of the dentition (Schwashman 1956). Tetracycline is a broad spectrum antibiotic, that has a special affinity for deposition in teeth and bones probably due to the formation of a tetracycline-calcium-phosphate complex (Letter-Eckman 1975). The teeth

are bright yellow upon eruption, which is the color of the tetracycline itself. The color gradually turns into dark brown after exposure to light, due to photo-oxydation of tetracycline into a redish product (Davies 1985). Chlor and oxy-tetracycline, homologies of tetracycline, discolor the teeth even more (Shallow 1967). Pigmentation of teeth has also been observed in children receiving other antibiotics e.g. erytromycin (Adno 1967). It is the physician's responsibility to avoid prescribing such drugs to pregnant women and to children up to 7-8 years old in order to prevent dental staining. Internal bleaching using hydrogen-peroxide, may lighten tetracycline stained teeth significantly (Hayashi 1980; Walton 1983). Internal bleaching requires a root canal therapy. Many authors recommended external (vital) bleaching techniques for teeth discolored due to tetracycline administration (Berman 1982). It is shown in an animal experiment, that internal bleaching is much more effective than external bleaching (Walton 1982 and 1983). Seale (1985) concluded from an epidemiological study, that external bleaching should only be applied for very mild tetracycline stains.

Dental fluorosis or 'mottled enamel', is an endemic dental disturbance seen in communities, where the fluoride content of the drinking water exceeds 1.5 ppm or when high levels of fluoride from other sources (F-tablets) have been received during development. Excess of fluoride during tooth development, causes hypomaturation of the enamel. Depending on its severity, the enamel stain varies from opaque white spots to yellow-brown or black patches (Kerr 1973; Colon 1973). Fluorotic stains are reduced by topical application of a mixture of hydrochloric acid and hydrogen-peroxide (whether or not in combination with ether) on the external tooth surfaces (Colon 1973; Boksman 1983; Seale 1985).

Post-eruptive discoloration

Tooth discoloration after tooth eruption can be due to aging, secundary dentin formation, erosion, attrition, etc (Rakow 1976). These 'normal physiological' color changes, vary from yellow to brown (Vogel 1975).

A trauma may cause rupture of the blood vessels in the pulp leading to hemorrhage into the pulp cavity (Cohen 1984). Pulpal hemorrhage results almost immediately in a pinkish tooth discoloration by the diffusion of the red hemoglobin pigment into the dentin (Grossman 1981). Due to the subsequent decomposition of hemoglobin, the initial pink discoloration progressively turns into grey within 2 weeks (Goldstein 1976; Jacobsen, 1980). On the other hand, a traumatic injury may suddenly obstruct the blood supply of the pulp. The absence of blood circulation, induces ischemic pulp necrosis (Stanley 1978). As a result of the decomposition of necrotic pulp tissue, a greyish discoloration appears gradually during several months (Jacobsen 1980). For internal bleaching of discolorations induced by necrotic pulp tissue or blood components, the prognosis is reasonably good (Cohen 1984).

Intrinsic stain is also observed in connection with caries (Rakow 1976; Goldstein 1976). The irregularity of the decayed surface, probably stimulates the retention of colored substrates that are present in the oral cavity. In case the lesion reaches as far as the dentin, the colored substrates might easily penetrate into the dentinal tubuli.

Discoloration of the dentition as a result of dental therapy, is referred to as iatrogenic discoloration. Unfortunately, iatrogenic discoloration is still regularly observed. Leakage of a restoration, for example, may be responsible for intrinsic tooth discoloration. Intrinsic staining of teeth is also effectuated by inaccurate endodontic technique

(Nicholls 1977). Failure to stop bleading or to remove all remnants of necrotic pulp tissue, results in similar discolorations as observed after trauma.

Another cause of tooth discoloration following dental treatment, is the use of discoloring materials. The elimination of stains from dental materials using the currently available bleaching products, is believed to be difficult (Nicholls 1977). The dentin can acquire a greenish-grey to black stain from corrosion of amalgam restorations by galvanic action (Vogel 1975). In an electron microscopic study, the discoloration was observed to be caused by migration of tin ions into the dentin (Wei 1969). Furthermore, amalgam stain likely occurs under thin dentinal walls where the filling material is reflected through the dentin and enamel (Grossman 1981). Stains from amalgam are prevented by placing a base or cavity liner (Fain 1961). In addition, many endodontic drugs and filling materials are suspected of causing discoloration (Goerig 1974; Ingle 1976; Nicholls 1977). To select proper materials for root canal therapy, reliable information about their staining properties is required. Information on the staining potential of endodontic materials as provided in dental literature, however, is often contradictory or incomplete. Presumably the disagreement between authors accrues from the lack on research on this topic. Basically, the prevention of discolorations produced by endodontic materials is within reach of the dentist. Therefore, the staining potentials of those materials have to be thoroughly investigated.

TECHNIQUE FOR INDUCING REPRODUCIBLE INTRINSIC DISCOLORATION IN EXTRACTED HUMAN TEETH[1]

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II.3.1. SUMMARY

An in-vitro technique was developed for producing measurable and reproducible coronal color changes in teeth. The difference was assessed between 2 methods to prevent dehydration of enamel and associated access preparations. The relative discoloration in freshly extracted teeth and teeth stored in ethanol, was also compared. The most reproducible results were obtained with water immersion for humidity control and an apical access to the pulp chamber. Freshly extracted teeth or teeth stored in ethanol, seemed to work equally as well for determining relative staining of the tooth crown as compared to the original tooth color. The technique could be applied for studies on the discoloring properties of endodontic materials.

II.3.2. INTRODUCTION

Tooth discoloration as a result of endodontic treatment, is a common esthetical problem in dentistry. Such discolorations are localized within the tooth structure (Vogel 1975). Internal tooth discoloration is referred to as intrinsic discoloration, as opposed to extrinsic discoloration indicating stain accumulation on the tooth surface (Spouge 1973).

The main etiological factors of tooth discoloration related to endodontic treatment are: decomposition of necrotic pulp tissue, hemorrhage into the pulp cavity, and endodontic drugs and filling materials (Ingle 1976). Darkening of teeth after endodontic treatment can often be prevented by careful endodontic technique and selecting medicaments and sealing agents with a minimal potential of staining. Most of the research on tooth discoloration, however, is concerned with extrinsic discoloration, or intrinsic discoloration produced during the stages of tooth formation. Gutiérrez (1968) examined staining of dentin discs caused by local application of several antibiotics and disinfectants. No other studies on discoloring properties of endodontic materials could be found in literature.

The present paper describes the development of an in-vitro technique for producing measurable and reproducible coronal color changes in teeth. The influence of 2 variables on the discoloration process was investigated. The first variable concerns maintenance of the moisture content in enamel, either by immersion in water (access opening apically) or by storage at 100% humidity (access opening coronally). The second variable is the method of storage of the teeth after extraction, either in water or in a preservative solution. Ultimately, this technique will serve as a basis for investigating the staining potentials of various dental materials.

[1]Int Endod J: accepted for publication, 1985

II.3.3. MATERIALS AND METHODS

Preparation of teeth

Sound human premolars, extracted for orthodontic reasons, were used. After cleaning and polishing the external surfaces, the apical segment of the roots was removed. The pulps were extirpated through an access opening and the pulp chambers were instrumented. The original, pre-stain color of the tooth crowns was determined. Then the pulp chambers were irrigated successively with EDTA and NaOCl (Goldman 1982). Three percent NaOCl pH 11 (Thé 1979) and 0.3 M EDTA pH 5.5 (Cury 1981) were used. The pulp cavities were first filled with EDTA, followed after a 5 minutes interval by flushing with 5 ml EDTA using a syringe. This procedure was repeated twice with EDTA and subsequently 3 times with NaOCl. After irrigation, the teeth remained in distilled water for 48 hours at room temperature prior to staining.

Staining of teeth

The discoloring agent was a solution of blood components, consisting of a concentrated hemolysate containing 10% hemoglobin. Using a Pasteur's pipette, the hemoglobin solution was introduced into the pulp cavities of experimental teeth. The control teeth were filled with distilled water. All samples were incubated at 37°C. The next 4 days, the tooth color was determined daily, after which each time the hemoglobin solution was renewed to restrain bacterial growth. Following the 4th day color reading, the staining agent was removed from the pulp chamber using paper points. During the remaining incubation period, the pulp cavities were kept free of liquid. Subsequent color assesments were performed after 10 and 25 days.

Color determination and data processing

The following visual method was employed for quantification of the tooth colors, which has been shown to give reliable results (chapter I.3.). Light source, lighting intensity, environment, and background were standardized as decribed previously. Only with respect to the position of the teeth to be evaluated, a minor modification was introduced. Instead of in a phantom head, the teeth were placed on a white sheet.

The color of the mid-cervical part of the labial tooth surfaces was matched, using a set of color standards. The standards were arranged according to the 3 visual color dimensions: Hue, Value, and Chroma (Munsell 1961). Hue or shade is the quality of color which is described by the words yellow, red, green, etc. Value or brightness is the degree of grey, varying between black and white (figure 1 chapter II.4.). The term Chroma indicates intensity or saturation of the color. Basically, 7 Hue, 8 Value, and 6 Chroma steps could be distinguished in the set of color standards.

The standards were held adjacent to the labial tooth surface. Both surfaces were viewed simultaneously through 2 holes (diameter 4 mm) in a neutral grey shield. The shield was kept parallel to the tooth surface at a 30 mm distance (figure 2 chapter II.4.). All color assessments were done by 2 independent observers, whose color visions were found to be normal by the 100 Hue Farnsworth-Munsell test. In case of disagreement the color was reassessed.

The color standards were analyzed spectrophotometrically. From the reflection curves obtained, color coordinates L^*, u^*, and v^* of the approximately uniform CIELUV color space were computed (CIE 1976). Standards with $54.0 < L^* < 86.0$, $3.0 < u^* < 62.0$, and $5.0 < v^* < 58.0$ were used. To facilitate interpretation of these physical color specifications, all data were transformed to Hue, Value, and Chroma indications

(CIE 1976). For the statistical analysis of the color differences, a t-test for correlated data was used.

Variables

The influence of the following variables was investigated: (a) the access preparation and associated maintenance of moisture content and (b) the method of storage of teeth.

Ad a: Two directions of access preparation were compared, occlusal and apical (as illustrated in figures 1 and 2, respectively) with associated methods of humidity control. Freshly extracted teeth were used, 10 experimental teeth and 6 control teeth were prepared apically. An occlusal access was prepared in 5 experimental teeth and 3 controls.

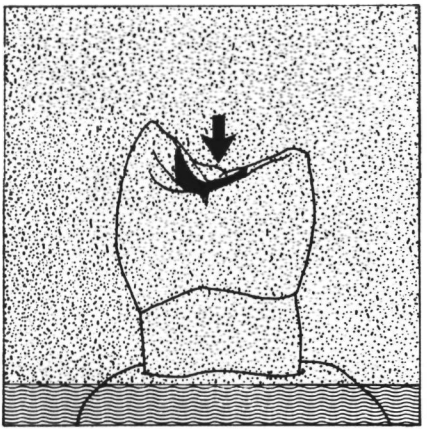

FIGURE 1:
Occlusal access preparation. The apical opening was closed with soft wax and the teeth were placed crown-upwards in a test room at 100% humidity atmosphere. Dotted area = 100% humidity; wavy area = water.

Ad b: Discoloration patterns in 10 freshly extracted premolars were compared to 10 premolars stored in ethanol for unknown time. The freshly extracted teeth were stored in water at 4°C immediately after extraction; they were prepared within 2 weeks. The teeth stored in ethanol remained in water at room temperature for a minimum of 2 weeks between instrumentation and irrigation. Both groups of teeth were prepared with an apical access preparation. Each group was completed with 6 control teeth.

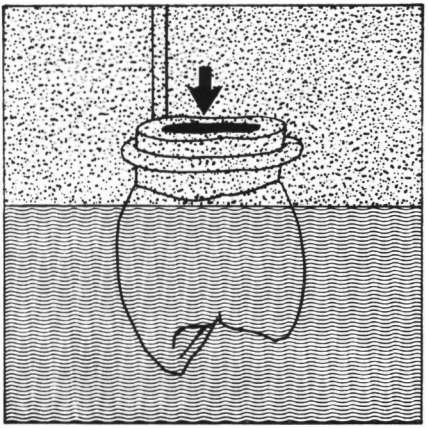

FIGURE 2:
Apical access preparation. A ligature wire was fixed on the cervix and the teeth were hung root-upwards in a test tube containing distilled water. The coronal portions were immersed in water. The tubes were closed with a cap to which the wire was attached. Dotted area = 100% humidity; wavy area = water.

II.3.4. RESULTS

Results obtained with the occlusal access and associated humidity control, differed in some respects from results obtained with an apical access and water immersion for moisture control. In table 1 is demonstrated that the patterns of Hue-scores were slightly different. Furthermore, this table shows that the ultimate Chroma-scores were considerably lower for experimental teeth prepared with an occlusal access. In addition, the Value and Chroma of occlusally prepared control teeth was not stable during the period examined (table 1).

Moreover, 2 complications interfering with the color readings on occlusally prepared teeth were observed. First, only the cervical part of the tooth crowns discolored. Second, the enamel gradually became fairly dull and white spotted.

Table 2 shows a decrease in Hue-score at the first days of the staining procedure; the Hue-score decreased as compared to the pre-stain Hue. Within 10 days, the Hue-score gradually reached the original Hue again. Such pattern of Hue-scores, corresponds with a visual sensation of a temporary color shift from yellow towards red. This pattern was observed for freshly extracted teeth and teeth stored in ethanol, both having an apical access preparation to the pulp cavity.

For all apically prepared teeth, freshly extracted and stored in ethanol, the Value-score diminished equally, immediately after introduction of the hemoglobin solution (table 2). The scores remained on this lower level. A lower Value-score indicates that the color of the teeth appears to be darker.

Concerning the Chroma-score, no specific pattern could be detected (table 2), except that for both groups of teeth the Chroma-score after application of the blood components, was equal to or somewhat lower than the original Chroma. A lower Chroma-score is correlated to a lower saturation. This implies that the saturation of the tooth color was unchanged or became slightly less saturated as compared to the pre-stain color.

The color of all control teeth, having an apical access to the pulp chamber, was constant for the 3 color dimensions during the period examined (table 2).

II.3.5. DISCUSSION

The purpose of this study was to develop a discoloring technique for investigating the staining substances involved in clinical endodontics. The method, therefore, should be suitable for liquid as well as for solid substances (e.g. blood, filling materials). Freccia (1982) designed an in-vitro technique for staining of teeth using blood components, to obtain samples for bleaching studies. The teeth were totally immersed in blood and centrifuged twice each day to hasten the discoloration process. Although severe staining of extracted teeth was induced after 6 days, his technique can not be applied for solid materials. In contrast to Freccia's technique, in the technique described in this paper, the staining material was applied into the pulp cavities, whereas the determination of coronal color changes was performed on the external tooth surfaces. A solution of blood components was also choosen as staining agent, since pulpal hemorrhage after trauma is likely to be the prime factor for deep tooth discoloration (Cohen 1984). It has been shown recently (chapter II.4.), that this newly developed method is suitable for testing the staining potentials of endodontic sealers.

TABLE 1:
Average color-scores before (original) and after introduction (1,2,...,25 days) of a hemoglobin solution for freshly extracted teeth having an apical or an occlusal access preparation. The color-scores are expressed in terms of Hue, Value, and Chroma ± standard deviation.

	Freshly extracted teeth			
	Apical access		Occlusal access	
	Control(n=6)	Blood(n=10)	Control(n=3)	Blood(n=5)
	HUE		HUE	
original	0.96 ± 0.02	0.97 ± .03	1.01 ± 0.03	0.99 ± 0.04
day 1	0.96 ± 0.02	0.75 ± .07*	1.02 ± 0.05	0.74 ± 0.03*
day 2	0.97 ± 0.02	0.79 ± .05*	0.98 ± 0.03	0.76 ± 0.05*
day 3	0.96 ± 0.02	0.85 ± .07*	1.00 ± 0.04	0.75 ± 0.05*
day 4	0.97 ± 0.02	0.83 ± .06*	1.00 ± 0.04	0.74 ± 0.05*
day 10	0.97 ± 0.02	0.95 ± .03*	0.99 ± 0.03	1.00 ± 0.07
day 25	0.96 ± 0.02	0.96 ± .02	0.99 ± 0.03	0.98 ± 0.01
	VALUE		VALUE	
original	74.1 ± 0.9	73.8 ± 2.4	74.4 ± 0.3	74.3 ± 1.0
day 1	74.2 ± 0.7	62.2 ± 3.5*	78.6 ± 3.8	65.3 ± 0.2*
day 2	73.7 ± 1.0	62.5 ± 5.0*	77.7 ± 3.0	63.3 ± 4.4*
day 3	74.1 ± 0.9	61.2 ± 2.6*	79.8 ± 1.1*	58.5 ± 4.3*
day 4	74.0 ± 0.9	60.0 ± 3.0*	79.8 ± 1.1*	59.6 ± 5.4*
day 10	74.2 ± 0.6	60.2 ± 2.0*	79.5 ± 0.8*	62.4 ± 1.9*
day 25	73.9 ± 1.1	60.0 ± 1.8*	79.5 ± 0.8*	62.4 ± 2.6*
	CHROMA		CHROMA	
original	0.56 ± 0.02	0.57 ± 0.06	0.54 ± 0.01	0.55 ± 0.03
day 1	0.56 ± 0.01	0.51 ± 0.13	0.46 ± 0.09	0.32 ± 0.01*
day 2	0.57 ± 0.02	0.50 ± 0.13	0.45 ± 0.09	0.32 ± 0.01*
day 3	0.56 ± 0.02	0.46 ± 0.10*	0.40 ± 0.01*	0.33 ± 0.01*
day 4	0.56 ± 0.02	0.52 ± 0.09	0.40 ± 0.01*	0.33 ± 0.02*
day 10	0.56 ± 0.01	0.51 ± 0.05*	0.40 ± 0.01*	0.29 ± 0.03*
day 25	0.57 ± 0.03	0.51 ± 0.04*	0.40 ± 0.01*	0.30 ± 0.01*

Hue: + = more yellow and - = more red. Value: + = brighter and - = darker. Chroma: + = intenser and - = less saturated. * significant difference compared to original tooth color ($p < .01$).

TABLE 2:
Average color-scores before (original) and after introduction (1,2,...,25 days) of a hemoglobin solution for freshly extracted teeth or teeth stored in ethanol having an apical access preparation. The color-scores are expressed in terms of Hue, Value, and Chroma ± standard deviation.

	Apical access preparation			
	Freshly extracted teeth		Teeth stored in ethanol	
	Control(n=6)	Blood(n=10)	Control(n=6)	Blood (n=10)
	HUE		HUE	
original	0.96 ± 0.02	0.97 ± 0.03	1.18 ± 0.02	1.18 ± 0.02
day 1	0.96 ± 0.02	0.75 ± 0.07*	1.18 ± 0.02	0.90 ± 0.06*
day 2	0.97 ± 0.02	0.79 ± 0.05*	1.18 ± 0.02	0.93 ± 0.09*
day 3	0.96 ± 0.02	0.85 ± 0.07*	1.18 ± 0.02	0.99 ± 0.04*
day 4	0.97 ± 0.02	0.83 ± 0.06*	1.18 ± 0.02	0.99 ± 0.06*
day 10	0.97 ± 0.02	0.95 ± 0.03*	1.18 ± 0.02	1.20 ± 0.02
day 25	0.96 ± 0.02	0.96 ± 0.02	1.18 ± 0.02	1.18 ± 0.01
	VALUE		VALUE	
original	74.1 ± 0.9	73.8 ± 2.4	84.6 ± 4.0	81.5 ± 4.1
day 1	74.2 ± 0.7	62.2 ± 3.5*	85.5 ± 3.3	64.8 ± 3.2*
day 2	73.7 ± 1.0	62.5 ± 5.0*	84.6 ± 4.0	63.8 ± 2.5*
day 3	74.1 ± 0.9	61.2 ± 2.6*	84.2 ± 4.0	62.6 ± 2.2*
day 4	74.0 ± 0.9	60.0 ± 3.0*	85.5 ± 3.7	61.6 ± 3.6*
day 10	74.2 ± 0.6	60.2 ± 2.0*	85.0 ± 3.5	65.5 ± 3.1*
day 25	73.9 ± 1.1	60.0 ± 1.8*	84.2 ± 4.0	62.8 ± 3.3*
	CHROMA		CHROMA	
original	0.56 ± 0.02	0.57 ± .06	0.38 ± 0.06	0.42 ± 0.04
day 1	0.56 ± 0.01	0.51 ± .13	0.38 ± 0.06	0.39 ± 0.05
day 2	0.57 ± 0.02	0.50 ± .13	0.38 ± 0.06	0.37 ± 0.06
day 3	0.56 ± 0.02	0.46 ± .10*	0.37 ± 0.06	0.39 ± 0.06
day 4	0.56 ± 0.02	0.52 ± .09	0.38 ± 0.06	0.41 ± 0.06
day 10	0.56 ± 0.01	0.51 ± .05*	0.38 ± 0.06	0.37 ± 0.03*
day 25	0.57 ± 0.03	0.51 ± .04*	0.37 ± 0.06	0.35 ± 0.03*

Hue: + = more yellow and - = more red. Value: + = brighter and - = darker. Chroma: + = intenser and - = less saturated. * significant difference compared to original tooth color ($p < .01$).

Special attention was given to the prevention of desiccation of the enamel during the staining procedure. Dehydration drastically changes the optical properties of enamel resulting in a loss of translucency (ten Bosch 1979). Because enamel becomes white and opaque after dehydration, the color of the underlying dentin will become less detectable. Two types of access preparations and associated methods for humidity control were investigated (figures 1 and 2). The technique characterized by an occlusal access preparation to the pulp cavity, showed a number of disadvantages as compared to the technique with an apical access. First, the storage at 100% humidity, as used for the occlusally prepared teeth, did not prevent desiccation of the enamel. This explains the color variations observed in controls (table 1). Possibly the less saturated colors, found for occlusally prepared experimental teeth, could be caused by dehydration of the enamel (table 1). Second, only the cervical part of the crowns was discolored for the teeth having an occlusal access opening. Apparently, the hemoglobin did not diffuse into the dentinal tubules located above the fluid level. It can be concluded that optimal results were obtained with water immersion for humidity control and an apical access to the pulp chamber.

Another variable investigated was the use of freshly extracted teeth versus teeth stored in preservatives. No essential difference in discoloration pattern was observed between freshly extracted teeth and teeth stored in ethanol. For both groups of teeth, similar color changes were recorded for Hue, Value, and Chroma as compared to the original color (table 2). Only the Hue and Value changes were more pronounced in teeth stored in ethanol.

A general impression of the experimentally induced tooth discoloration can be obtained by combining the Hue, Value, and Chroma-scores in a descriptive way. Initially the tooth color shifted towards red, whereas eventually the color became more grey as compared to the original tooth color. This pattern of discoloration resembles clinically observed discoloration in traumatized anterior teeth. According to Jacobsen (1980), a tooth becomes pink almost immediately after traumatic injury turning progressively to greyish within approximately 2 weeks. The following explanation can be given: Tooth discoloration after trauma is effected by rupture of blood vessels leading to hemorrhage into the pulp chamber (Cohen 1984). The red hemoglobin pigment is released upon lysis of erythrocytes. This pigment penetrates into the dentinal tubules causing the initial pink discoloration of the tooth crown (Grossman 1981). Subsequently, dark colored derivates are produced by decomposition of hemoglobin, causing a color shift from pink to grey (Goldstein 1976). Fresh hemolysate, as used in the experimental discoloration process, contains all components for hemoglobin breakdown (Bonting 1966). It is assumed that similar mechanisms are involved in clinical and experimentally induced tooth discoloration.

The diameter of the dentinal tubules decreases with increasing age due to the formation of secondary dentin (Nalbandian 1960). The size of the tubules may influence the permeability of the dentin. For this study, premolars extracted for orthodontic reasons were used because those teeth were all expected to have about the same permeability of dentin.

Due to instrumentation, a 'smeared layer' of dentinal debris will be disposited on the wall of the pulp cavity (McComb 1975). Such a layer probably causes reduced permeability of dentinal tubules by mechanical obstruction (Anderson 1962; Pashley 1978). To provide optimal diffusion of the hemoglobin into the dentin, the smeared layer was dissolved by alternate irrigation with EDTA and NaOCl solutions (Goldman 1982). To eliminate remnants of EDTA and NaOCl, the irrigated teeth remained in water

for 2 days preceding the staining procedure.

A slight change in tooth color, was recorded immediately after the irrigation procedure (unpublished data). This color change is probably caused by the bleaching action of NaOCl. The change, however, was only temporary as demonstrated in control teeth. Therefore, the reference color of the tooth should preferably be determined before irrigation, or the teeth should remain in water for a longer period after irrigation.

II.3.6. CONCLUSIONS

Measurable significant color changes of the tooth crowns, were produced using the technique described. The most reproducible results were obtained with water immersion for humidity control and an apical access to the pulp chamber. The pattern of discoloration, obtained using the immersion technique, resembles clinically observed tooth discoloration after traumatic injury. Furthermore, freshly extracted teeth or teeth stored in ethanol, seemed to work equally as well for determinating relative staining of the tooth crown as compared to the original tooth color. This technique could be applied for studies on the discoloring properties of endodontic materials.

TOOTH DISCOLORATION INDUCED BY ENDODONTIC SEALERS[1]

T.P. van der Burgt, T.P. Mullaney* and A.J.M. Plasschaert (University of Nijmegen, The Netherlands and *University of Kentucky, USA)

II.4.1. ABSTRACT

Endodontic therapy often results in discoloration of the tooth crown. The main etiologic factors are: blood, necrotic pulp tissue, and endodontic materials. The staining potentials of various materials were examined in-vitro using a visual method for tooth color determination. Extracted premolars were prepared and the following sealers were introduced into the pulp cavities: Zinc-oxide Eugenol cement, Grossman's cement, AH26, Diaket, N2, Riebler's paste, Tubli-Seal and Endomethasone. Before the sealers were applied, the original tooth colors were assessed on the external buccal tooth surfaces. Further color determinations were performed at regular intervals up to 6 months after introduction of the sealers. Each material induced measurable tooth discoloration within 3 weeks. Riebler caused the most severe discoloration, Diaket gave a mild stain. The other materials produced intermediate discolorations between those of Riebler and Diaket.

II.4.2. INTRODUCTION

Tooth discoloration as a result of endodontic treatment, is a common esthetical problem in clinical dentistry. The principle causes of intrinsic tooth discoloration related to endodontic treatment are: decomposition of necrotic pulp tissue, hemorrhage into the pulp cavity, and endodontic drugs and filling materials (Nicholls 1977). Darkening of tooth crowns after root canal therapy, can often be prevented by careful endodontic technique and selecting medicaments and sealing agents with a minimal potential of staining (Ingle 1976).

In most endodontic textbooks, it is recommended to avoid the use of discoloring materials in endodontics. For selecting proper materials, reliable information about their staining properties is required. However, the information on the staining potentials of endodontic materials provided in dental literature, is often contradictory or incomplete. According to Thoden van Velzen (1973), for example, Diaket does not discolor tooth structure. On the contrary, Goerig (1974) assigned Diaket in the moderate staining category of root canal sealers, whereas Grossman (1981) did not mention the staining potentials of Diaket. Presumably, the disagreement between the authors accrues from the lack of research on this topic. Only the staining of dentin discs, caused by local application of several antibiotics and disinfectants formerly used in endodontics, was examined (Gutièrez 1968). A review of literature revealed no additional studies concerning the staining potentials of endodontic materials.

The present paper reports an in-vitro investigation on the discoloring properties of 8 endodontic sealers, whether or not in combination with blood. For this study, a previously developed technique for inducing intrinsic tooth discoloration (chapter II.3.) and a new method for tooth color quantification (chapter I.3.) were applied.

[1]Oral Surg: accepted for publication, 1985

II.4.3. MATERIALS AND METHODS

Preparation of teeth

Sound human premolars, extracted for orthodontic purposes, were used. After cleaning and polishing the external surfaces, the apical segment of the roots was removed. The pulps were extirpated and the pulp chambers instrumented through an apical access (chapter II.3.). Then the pulp chambers were irrigated successively with EDTA and NaOCl (Goldman 1982). After irrigation, the teeth were kept in distilled water for 1 week at 37°C. The original tooth colors were assessed prior to the staining procedure.

Staining of teeth

Before the endodontic materials were applied into the teeth, the pulp cavities were dried using paper points. A ligature wire was fixed on the cervix of the teeth and the teeth were hung root-upwards in a test tube containing distilled water. To control the moisture content in the enamel, the coronal portions were immersed in water (figure 2 chapter II.3.). The bottles were closed with a cap, to which the wire was attached. The samples were coded randomly and incubated at 37°C. The next 4 days, the tooth color was determined daily; further color determinations were performed weekly up to the 7th week color reading. For group A, a final color evaluation was done after 6 months. After the last color determination, the samples were decoded.

The staining potentials of the following endodontic sealers were examined: Zinc-oxide Eugenol cement (Kraepelien & Holin, Bussum, The Netherlands), Grossman's non-staining cement (Standard Dental Products, 's Gravenhage, The Netherlands), AH26 (De Trey Dentsply, Zurich, Switzerland), N2 universal (Indrag AGSA, Losone, Switzerland), Riebler's paste (Wera Karl, Bissingen, BDR), Endomethasone (Septodont, Paris, France), Diaket (Espe GHBH, Seefelt, BDR) and Tubli-Seal (Sybron Kerr, Michigan, USA). The sealers were prepared as prescribed by the manufacturers.

Each sealer was introduced into the pulp cavities of 12 teeth, which were equally divided into 3 experimental groups as follows: Group A:- Freshly extracted premolars stored in water at 4°C immediately after extraction; Group B:- Premolars stored in ethanol. The teeth were kept in water at room temperature for a minimum of 1 month between instrumentation and irrigation; Group C:- As group B, but preceeding the introduction of sealers, the teeth were filled with a hemolysate solution (containing 10% hemoglobin) and incubated for 3 days at 37°C. An additional, hemoglobin stain, color determination was done after removal of this solution. The sealers were then introduced into the pulp cavities.

For every experimental group, 4 control teeth were taken. The pulp cavities of group A and B control teeth were filled with distilled water. The controls for group C were discolored by a hemolysate solution as described for experimental group C. During the remaining period, the pulp cavities of group C controls were empty.

Color determination

The following visual method was employed for determination of the tooth colors, which has been shown to give reliable results (chapter I.3.). Light source, lighting intensity, background, and environment were standardized as described previously. The teeth were placed on a white sheet.

The color of the mid-cervical part of the labial tooth surface was matched, using a set of color standards. The standards were arranged according to the 3 visual color dimensions: Hue, Value, and Chroma (Munsell 1961). Hue or shade is that quality of color which is described by the words

yellow, red, green, etc. Value or brightness is the degree of grey. The term Chroma indicates intensity or saturation (figure 1). Basically 7 approximately equidistant Hue, 8 Value, and 6 Chroma steps could be distinguished in the collection of color standards. The set was not complete for all possible standards.

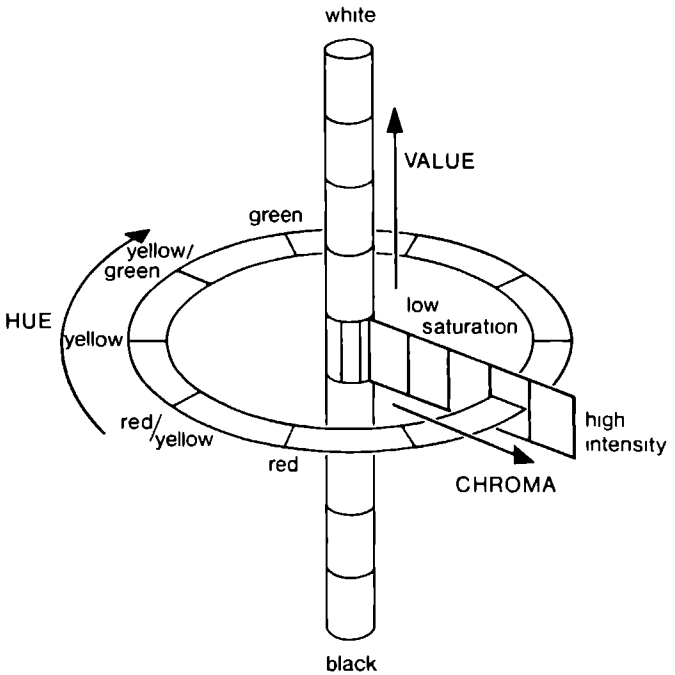

FIGURE 1:
Munsell system for color ordering (with permission of Munsell Color Corp, Baltimore, USA).

The standards were held adjacent to the labial tooth surface. Both surfaces were viewed simultaneously through 2 holes (diameter 4 mm) in a neutral grey shield. The shield was kept parallel to the tooth surface at a 30 mm distance using a special holder (figure 2). All color evaluations were performed by 2 independent observers, whose color visions were found to be normal by the 100 Hue Farnsworth-Munsell test. In case of disagreement, the color was re-assessed.

Data processing

The opaque color standards were analyzed spectrophotometrically. From the reflection curves obtained, color coordinates L*, u*, and v* of the approximately uniform CIELUV color space were computed (Hunter 1975; Driscoll 1978). Color standards with $55 < L^* < 91$, $2 < u^* < 63$, and $5 < v^* < 56$ were used. To facilitate interpretation of these physical color specifications, all data were transformed to Hue, Value, and Chroma indications (CIE 1976). The size of the interval between adjacent standards was minimal: 0.1 for Hue, 5.0 for Value, and 0.12 for Chroma.

Actually, using this method the color of a tooth is quantified indirectly by selecting a matching color standard. For statistical

analysis of the differences in tooth color, a t-test for correlated data was used.

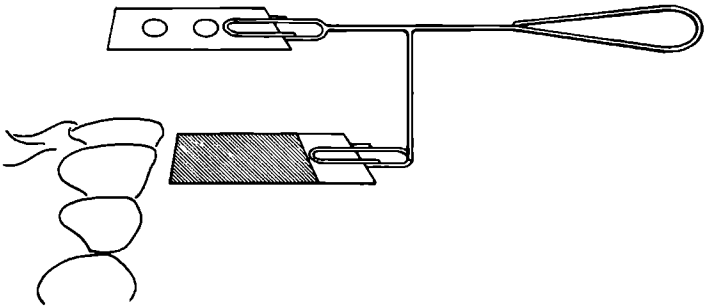

FIGURE 2:
Schematic reproduction of the visual method for tooth color determination.

II.4.4. RESULTS

For group A, the mean scores for Hue, Value, and Chroma with associated standard deviations are presented in table 1. Expressed in a descriptive way, the following discoloration patterns were observed for group A during 7 weeks: (1) In about 3 weeks, Diaket gave a mild pink stain. (2) AH26 induced a distinct color shift towards grey after 1 week. (3) Grossman's cement, Zinc-oxide Eugenol, N2, Tubli-Seal, and Endomethasone caused a moderate orange-red discoloration. The discoloration appeared within 1-4 days and proceeded gradually. (4) Riebler's paste produced a severe dark red stain almost immediately after filling. (5) During the examination period, no color changes were detected in control teeth.

For group A, the Hue, Value, and Chroma-scores obtained after 6 months were not essentially different from the color-scores after 7 weeks. Except for the teeth filled with Diaket, which initially became pink, whereas after 6 months the Hue-score reached the original Hue-score again.

In group A and B, similar relative color changes compared to the original tooth colors were found in 7 weeks for each endodontic sealer. The increase of the Chroma-scores was more pronounced for group B.

The Hue-scores after 7 weeks were comparable for group B and C. For group C the same Chroma-scores were recorded before and 7 weeks after staining, whereas for group B the Chroma-scores after staining were somewhat higher. Compared to group B, the post-stain Value-scores from group C were considerably lower. The decrease of the Value-scores was about the same for all experimental and control teeth from group C.

II.4.5. DISCUSSION

Each endodontic sealer examined, induced measurable tooth discoloration in freshly extracted premolars within 7 weeks (table 1), whereas the color of control teeth remained constant during this period. Goerig stated in 1974, that all endodontic sealers cause discoloration to some extent. He divided several sealers in 3 categories of staining: slight, moderate, and severe. If the sealers investigated in the present study, are arranged according to such classification the distribution is different. This perhaps arises from the fact that up to now no research data on this subject were available.

TABLE 1:
Average color-scores (N = 4; ± standard deviation) before and 7 weeks after introduction of the endodontic sealers.

	HUE		VALUE		CHROMA	
	original	7 weeks	original	7 weeks	original	7 weeks
Control	0.97 ±0.03	0.97 ±0.01	71.3 ±1.9	70.9 ±1.9	0.58 ±0.04	0.59 ±0.04
Grossman's cement	1.01 ±0.03	0.86 ±0.02**	71.3 ±1.1	67.8 ±2.5*	0.55 ±0.05	0.63 ±0.05*
Zinc-oxide Eugenol	0.99 ±0.02	0.86 ±0.02**	71.7 ±1.0	67.8 ±2.5	0.52 ±0.03	0.64 ±0.03*
Tubli-Seal	0.98 ±0.01	0.87 ±0.02**	69.3 ±1.2	68.5 ±2.2	0.60 ±0.03	0.55 ±0.12
Diaket	0.97 ±0.03	0.89 ±0.03*	71.2 ±4.8	70.2 ±2.6	0.58 ±0.13	0.58 ±0.10
AH26	0.97 ±0.03	0.96 ±0.00	72.0 ±0.7	64.6 ±1.5**	0.55 ±0.02	0.53 ±0.03
Endomethasone	0.96 ±0.03	0.84 ±0.02**	70.1 ±1.0	66.7 ±0.8*	0.59 ±0.05	0.60 ±0.06
N2	0.99 ±0.02	0.89 ±0.05*	70.7 ±1.7	69.1 ±2.4	0.57 ±0.06	0.61 ±0.05
Riebler's paste	0.93 ±0.04	0.58 ±0.02**	72.3 ±2.5	56.9 ±1.4**	0.51 ±0.07	0.70 ±0.05*

Score before > after : Hue = more orange-red ; Value = darker ; Chroma = less intense.
Score after > before : Hue = more yellow-green; Value = brighter; Chroma = intenser.
* significant difference compared to original tooth color (*$p < 0.05$; **$p < 0.01$).

All discolorations were visible within 3 weeks after application of the sealers. At subsequent color readings, minimal progression of staining was recorded. Apparently, the difussion of staining substances predominated before or during the first period after setting of the endodontic materials.

Possibly, the staining potential of various materials appears to be lower clinically than in the experimental situation. Mechanical preparation of pulp cavities results in the deposition of dentinal debris, the so-called 'smeared layer', on pulpal walls (McComb 1975). In the experimental teeth, the smeared layer was dissolved to provide optimal diffusion of staining materials into the dentinal tubuli. In clinical situations, commonly no attempts are made to remove the smeared layer before filling. The presence of this layer may interfere with the permeability of the dentin for discoloring agents.

Although endodontic sealers are supposed only to fill the root canals, sealer remnants are often left behind in the crown. In addition, even after removing the sealer by mechanical means, particles of the material could remain in the dentinal tubuli of the crown. For this reasons, the effect of endodontic sealers on coronal tooth discoloration was investigated.

Dispite the fact that it might be difficult to eliminate each trace of sealer, it is recommended to remove the material carefully from the crown immediately after filling the root canal. Staining materials perhaps diffuse into incisally directed tubuli (Kraus 1976) and sub-gingivally localized stain may show through cervically. Furthermore, possible recessions of the gums increases the length of the clinical crown. To prevent these problems from occurring, the sealer should be removed 2 mm below the level of the crown (Nicholls 1977).

The relative coronal discoloration induced by a hemoglobin solution, was found to be similar for freshly extracted teeth and teeth stored in ethanol (chapter II.3.). This does not necessarily implies, that the same holds for discolorations caused by other materials. Therefore, the staining potentials of endodontic sealers was examined for freshly extracted teeth and teeth stored in ethanol, referred to as group A and B, respectively. The results indicate that no essential difference in discoloration pattern was observed between group A and B.

It is possible that certain materials per se are slightly or non-staining, while in combination with blood they effectuate distinct discoloration of teeth due to specific reactions between sealer and blood components. Group C was introduced to simulate the contact between blood and filling materials, as occurring after a careless endodontic technique that did not include adequate initial access and coronal debridement. As group B, group C consisted of teeth stored in ethanol. The average color change to be attributed to blood components, was obtained from group C control teeth. After 7 weeks, the Hue-scores for the controls were equal to the original color, whereas slighty lower Chroma-scores and much lower Value-scores were recorded. These findings were in agreement with the results from a previous study on tooth discoloration caused by blood (chapter II.3.). From each sample of group C, the 'hemoglobin-stain share' was substracted from the total discoloration. The remaining discoloration was equal to or somewhat weaker than the discoloration in samples of group B filled with the same sealer. Therefore, it was concluded that no additional staining could be demonstrated after blood contamination. It should be considered that the decomposition of blood components was initiated 3 days before the sealers were introduced. Perhaps the sealers would show a different reaction with fresh blood.

The results obtained using this method, serve as encouragement to

extend the research on the staining properties of other dental materials. In addition, the results indicate that standardized intrinsic staining of teeth can be induced using various endodontic sealers. In view of this, the technique seems to be suitable for evaluating the effect of preventive or therapeutic treatments on tooth discoloration in-vitro. In this context, two subjects could be further investigated. First, the influence of varnishing the dentinal tubuli prior to filling. Second, the effectivity of conventional bleaching techniques in destaining specific discolorations.

Based on the results in this study, it is difficult to recommend particular sealers since each sealer caused measurable tooth discoloration. Diaket caused the least discoloration. Zinc-oxide Eugenol, Grossman's cement, Endomethasone, N2, Tubli-Seal, and AH26 induced moderate tooth discoloration and Riebler brought about severe staining. Under the experimental conditions, however, the discoloration caused by Diaket seemed to be temporary. Perhaps in future, when more reseach data concerning this topic are available, a non-staining sealer can be recommended. For the moment, the selection of endodontic sealers should be based mainly on other criteria e.g. microleakage and toxicity. The need for careful coronal debridement after root canal obturation, is re-inforced by this study.

TOOTH DISCOLORATION INDUCED BY DENTAL MATERIALS[1]

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II.5.1. ABSTRACT

Tooth discoloration after endodontic treatment, is frequently attributed to drugs and filling materials. In this in-vitro study, the staining potential of various dental materials was investigated by means of a visual method to determine tooth color. Extracted human premolars were prepared and the following materials were introduced into the pulp cavities: Cavit, Durelon, Dycal, Fletcher's cement, IRM, AH26- silver free, Gutta Percha, Duo Percha, Fuji ionomer, and Zinc-phosphate cement. Before the materials were applied, the original tooth color was assessed on the external buccal tooth surfaces. Further color determinations were undertaken at regular intervals for 6 months after the materials were introduced. Durelon, Fuji ionomer, Fletcher's cement, and Zinc-phosphate cement did not induce measurable tooth discoloration. Cavit, Dycal, Gutta Percha, and IRM caused a mild stain. For the teeth filled with AH26-silver free and Duo Percha, a moderate discoloration was recorded.

II.5.2. INTRODUCTION

The darkening of tooth crowns after root canal therapy, may be caused by the use of discoloring endodontic drugs and filling materials (Grossman 1981; Nicolls 1977). To prevent tooth discoloration, medicaments and sealing agents with a minimal potential of staining should be selected for endodontic treatment (Cohen 1984). Therefore, reliable information about the staining properties of dental materials is required.

Most authors agree that amalgam is contra-indicated to restore the lingual access of anterior teeth because of an almost predictable grey stain (Cohen 1984). The information on the staining properties of other materials is often contradictory or incomplete, which probably accrues from the lack of research on this subject.

In a previous in-vitro study, the potency of 8 root canal sealers to induce staining of dental tissue, was examined (chapter II.4.). The sealers were tested in a situation similar to clinical endodontics. The sealers were applied into pulp cavities of extracted human premolars, whereas the coronal tooth colors were evaluated on the external buccal surfaces. At regular intervals, the size and direction of the color changes were quantified (chapter I.3.). The results indicated that each sealer produced measurable discoloration within several weeks.

The aim of the present study is to test the discoloring potential of 10 materials, mainly used to apply in the coronal part of teeth; they include: permanent restorative materials, temporary filling materials, and materals used as a base or cavity liner.

II.5.3. MATERIALS AND METHODS

Preparation of teeth

Sound human premolars, extracted for orthodontic purposes, were used. The teeth were stored in tap water at 4°C immediately after extraction. After cleaning and polishing the external surfaces, the apical segment of

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the roots was removed (chapter II.3.). The pulps were extirpated and the pulp chambers instrumented through an apical access opening. The pulp chambers were then irrigated successively with EDTA and NaOCl (Goldman 1982). After irrigation, the teeth were kept in distilled water for 1 week at 37°C. The original tooth colors were assessed prior to the staining procedure.

Staining of teeth

The staining potential of the following materials was examined: AH26-silver free (De Trey Dentsply, Zurich, Switzerland),Cavit (Espe GMBH, Seefeld, BDR), IRM (Caulk Dentsply, Milford, USA), Durelon (Espe GMBH, Seefeld, BDR), Dycal (Caulk Dentsply, Milford, USA), Fletcher's cement (Keur & Sneltjens Dental MFG, Haarlem, The Netherlands), Gutta Percha (Sybron Kerr, Michigan, USA), Duo Percha (De Trey Dentsply, Zurich, Switzerland), Fuji ionomer (G-C Dental Industrial Co, Tokyo, Japan), and Zinc-phosphate cement (Standard Dental Products, 's Gravenhage, The Netherlands). The materials were prepared as prescribed by the manufacturers. The pulp cavities were dried using paper points, whereupon the materials were introduced through the apical access. Each material was applied into the pulp cavities of 4 teeth. Four control teeth were filled with distilled water.

A ligature wire was fixed around the cervix of the teeth and the teeth were hung root-upwards in a test tube containing distilled water. To control the moisture content in the enamel, the coronal portions were immersed in water (figure 2, chapter II.3.). The bottles were closed with a cap, to which the wire was attached. The samples were coded and incubated at 37°C. The tooth color was determined after 3, 7, 15, and 25 weeks. After the last color reading, the samples were decoded.

Color determination

The following visual method was employed for determination of the tooth colors, which has been shown to give reliable results (chapter I.3.). Light source, lighting intensity, background, and environment were standardized as described previously. The teeth were placed on a white sheet.

The color of the mid-cervical part of the labial tooth surface was matched, using a set of color standards. The standards were arranged according to the 3 visual color dimensions: Hue, Value, and Chroma (Munsell 1961). Hue or shade is that quality of color which is described by the words yellow, red, green, etc. Value or brightness is the degree of grey. The term Chroma indicates intensity or saturation (figure 1 chapter II.4.). Basically 7 approximately equidistant Hue, 8 Value, and 6 Chroma steps could be distinguished in the collection of color standards. The set was not fully complete for all possible standards.

The standards were held adjacent to the labial tooth surface. Both surfaces were viewed simultaneously through 2 holes (diameter 4 mm) in a neutral grey shield. The shield was kept parallel to the tooth surface at a 30 mm distance (figure 2 chapter II.4.). All color evaluations were performed by 2 independent observers, whose color visions were found to be normal by the 100 Hue Farnsworth-Munsell test. In case of disagreement the color was re-assessed.

Data processing

The opaque color standards were analyzed spectrophotometrically. From the reflection curves obtained, color coordinates L*, u*, and v* of the approximately uniform CIELUV color space were computed (Hunter 1975; Driscoll 1978). Color standards with $55 < L^* < 91$, $2 < u^* < 63$, and

$5 < v^* < 56$ were used. To facilitate interpretation of these physical color specifications, all data were transformed to Hue, Value, and Chroma indications (CIE 1976). The size of the interval between adjacent standards was minimal: 0.1 for Hue, 5.0 for Value, and 0.12 for Chroma.

Actually, the color of a tooth is quantified indirectly by selecting a matching color standard. For statistical analysis of the color differences, a t-test for correlated data was used.

II.5.4 RESULTS

The mean scores for Hue, Value, and Chroma after 15 weeks with associated standard deviations, are presented in table 1. Expressed in a descriptive way, the following discoloration patterns were observed: (1) No discolorations were recorded for the teeth filled with Durelon, Fuji ionomer, Fletcher's cement, and Zinc-phosphate cement. (2) Cavit gave a light to moderate yellowish-green stain. (3) Gutta Percha caused a mild pinkish tooth discoloration. (4) AH26-silver free and Duo Percha induced a distinct color shift towards grey. (5) The color of the tooth crowns filled with IRM and Dycal, became somewhat darker and more saturated. The teeth filled with IRM tended to discolor towards an orange-red direction; the teeth filled Dycal towards a yellowish-green direction. (6) During the examination period, no color changes were detected in control teeth.

All discolorations were visible within 3 weeks after filling and remained quite stable during the experimental period, except for the staining induced by Dycal, which was stronger 3-7 weeks after filling than at subsequent color readings.

Although the crowns were immersed in water, the enamel of all teeth filled with Duo Percha appeared to be dessicated after 7 weeks.

II.5.5. DISCUSSION

All discolorations of the teeth were detectable at the first color evaluation, which was performed 3 weeks after application of the materials. At subsequent color readings, minimal progression of staining was recorded. Apparently, the diffusion of staining substances predominated before or during the first period after setting of the materials.

Coronal discolorations were most pronounced cervically. This can be explained by the fact that the enamel layer narrows towards the cervix, while the thickest bulk of dentin is localized in this area. Since enamel is a translucent and rather colorless material and the dentin of intrinsically discolored teeth is stained, the discoloration is reflected stronger at the cervial part of the crown.

Possibly the staining potential of the materials appears to be lower clinically. Mechanical preparation of pulp cavities results in the deposition of dentinal debris, the so-called "smeared layer" on pulpal walls (McComb 1975). In the experimental teeth, the smeared layer was dissolved to provide optimal diffusion of staining materials into the dentinal tubuli. Generally, in clinical situations, no attempts are made to remove the smeared layer before filling. The presence of a smeared layer may interfere with the permeability of the dentin for discoloring agents.

The appearance of a tooth depends on it's color and also it's opacity. Due to dehydration, the translucency of non-vital teeth is often reduced (Grossman 1981). The translucency of the crowns can be influenced by the application of filling materials. Some materials may induce additional loss of translucency by further dehydration of dental tissue. For example, the teeth filled with Duo Percha desiccated obviously. Other filling

TABLE 1:
Average color-scores (N = 4; ± standard deviation) before and 15 weeks after introduction of the dental materials.

	HUE		VALUE		CHROMA	
	original	15 weeks	original	15 weeks	original	15 weeks
Control	1.01 ±0.06	1.00 ±0.06	68.8 ±2.6	68.2 ±2.9	0.52 ±0.03	0.54 ±0.03
Cavit	0.98 ±0.01	1.05 ±0.02*	71.1 ±1.1	72.5 ±1.1	0.51 ±0.08	0.57 ±0.05
IRM	0.99 ±0.03	0.96 ±0.00	71.7 ±1.4	68.8 ±0.8*	0.54 ±0.09	0.65 ±0.06*
Durelon	0.99 ±0.03	0.99 ±0.03	72.2 ±1.2	70.2 ±2.0	0.53 ±0.08	0.54 ±0.03
Fuji ionomer	1.02 ±0.05	1.01 ±0.05	71.8 ±1.6	69.9 ±0.6	0.56 ±0.05	0.56 ±0.07
Fletcher's cement	0.99 ±0.02	0.98 ±0.03	70.0 ±1.2	68.3 ±1.0	0.54 ±0.09	0.56 ±0.07
Duo Percha	1.02 ±0.02	1.00 ±0.02	71.8 ±0.9	65.7 ±1.9**	0.56 ±0.02	0.49 ±0.05
Gutta Percha	1.02 ±0.05	0.98 ±0.03*	72.7 ±1.7	69.5 ±2.8	0.52 ±0.03	0.55 ±0.05
Zinc-phosphate cement	1.03 ±0.06	1.04 ±0.05	73.1 ±2.7	71.3 ±1.1	0.53 ±0.06	0.53 ±0.04
AH26-silver free	1.04 ±0.01	1.02 ±0.05	70.3 ±1.9	65.9 ±1.1**	0.58 ±0.06	0.54 ±0.06
Dycal	1.01 ±0.05	1.04 ±0.05	72.7 ±0.05	70.0 ±1.0*	0.51 ±0.07	0.63 ±0.05**

Score before > after: Hue = more orange-red ; Value = darker ; Chroma = less intense.
Score after > before: Hue = more yellow-green; Value = brighter; Chroma = intenser.
* significant difference compared to original tooth color (*$p < 0.05$; **$p < 0.01$).

materials could perhaps correct the increased opacity of non-vital teeth. The effect of the filling materials on the opacity, however, was not investigated in this study. When discoloration studies are continued in in-vivo, research on this aspect should certainly be included.

Under the experimental conditions, the amount of discoloration due to Dycal decreased in course of time. A similar observation was done before, for discoloration induced by Diaket (chapter II.4.). During the incubation period, direct contact existed between the investigated materials and the environment. Possibly initially formed colored complexes desintegrated afterwards; for example under influence of oxygen or water. On the other hand, the colored complexes could have evaporated or diffused from the teeth gradually. On a clinical basis, Dycal and Diaket are exluded from the oral cavity, because they are covered by other materials.

AH26-silver free is a recent modification from the conventional root canal sealer AH26, which contains silver. Conventional AH26 was demonstrated to cause a distinct grey discoloration of tooth crowns (chapter II.4.). The average drop in Value-score was 7.5 after 7 weeks. The grey stain was supposed to be due to silver ions (Dayan 1983). Therefore, it was expected that the elimination of silver, would reduce the staining properties of AH26. The results of this study, however, show that AH26-silver free induced a grey tooth discoloration as well. The mean Value difference recorded after 7 weeks was 4.4. Suprisingly, the presence of silver ions in AH26 was not exclusively reponsible for the darkening of tooth crowns.

Significant color differences in table 1, can be distinguished readily visually. Based on the results of this study, therefore, the following preliminary recommendations can be given. Before definitive statements are permitted, however, the results of this in-vitro study should be verified in clinical experiments.

In view of the discoloring properties, it may be concluded that Durelon and Fletcher's cement are preferably over Cavit, Duo Percha, Gutta Percha, and IRM as a temporary filling material in crowns of anterior teeth. Dispite the intensely colored appearence of the material itself, Gutta Percha causes only a mild pinkish stain.

To prevent discoloration of anterior teeth, Zinc-phosphate cement and Durelon are perhaps more suitable cements than Dycal, since the latter induces a mild stain. Nevertheless, it should be considered that the acidic Zinc-phosphate cement has an irritating effect on pulp tissue.

Fuji ionomer, the only permanent filling material investigated in this study, did not induce measurable discoloration of tooth crowns. In this context, it should be mentioned that the staining potentials of various composites and other permanent filling materials, have to be examined in future studies. Of course many other criteria (e.g. leakage) play an important role in selecting suitable materials for filling teeth.

STAINING PATTERNS IN TEETH DISCOLORED BY ENDODONTIC SEALERS[1]

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II.6.1. ABSTRACT

The use of discoloring endodontic materials, leads to intrinsic discoloration of teeth. In view of prevention and therapy of tooth discoloration, the staining patterns inside discolored teeth were investigated in-vitro. Extracted premolars were discolored using the following endodontic sealers: Grossman's cement, Zinc-oxide Eugenol, Diaket, Tubli-Seal, AH26, Endomethasone, N2, and Riebler's paste. The sealers were introduced into the pulp cavities and the color of the external buccal tooth surfaces was determined before and 6 months after introduction of the sealers. All materials produced measurable coronal discoloration. The discolored tooth crowns were hemi-sectioned and internal staining patterns were studied. For all teeth, the dentin was found to be partly to entirely stained. No discoloration could be observed in the enamel. For each material, the internal staining patterns were in agreement with the discolorations observed on the external surfaces.

II.6.2. INTRODUCTION

Discolorations localized within the tooth structure are referred to as intrinsic discolorations, as opposed to extrinsic discolorations indicating stain accumulation on the tooth surface (Spouge 1973). Darkening of tooth crowns after root canal therapy, is often attributed to the use of discoloring endodontic drugs and filling materials (Nicholls 1977; Grossman 1981). In a previous study, the discoloring potential of 8 endodontic sealers was investigated in-vitro (chapter II.4.). The sealers were introduced into the pulp cavities of extracted human premolars; the coronal color changes were evaluated at the external buccal surfaces. The results showed each material to produce measurable discoloration at the outside of intact tooth crowns within several weeks.

With respect to the prevention of, and therapy for intrinsic discolorations induced by endodontic materials, knowledge of the internal staining patterns might be of importance. Discoloring components of dental materials are assumed to penetrate from the pulp cavity into the dentin (Vogel 1975). The stained dentin will then be reflected through the enamel. A review of literature did not reveal studies on the appearance of staining patterns in teeth, discolored by root canal sealers. The aim of the present study, therefore, was to study staining patterns in dental hard tissues, experimentally discolored with endodontic sealers.

II.6.3. MATERIAL AND METHODS

Preparation of discolored teeth

Sound human premolars, extracted for orthodontic purposes, were used. The teeth were stored in tap water at 4°C immediately after extraction. After cleaning and polishing the external surfaces, the apical segment of the roots was removed until 3 mm below the crown-root junction. The pulps were extirpated and the pulp chambers instrumented through the apical access opening (chapter II.3.). To dissolve the smeared layer, the pulp

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chambers were irrigated successively with EDTA and NaOCl. After irrigation the teeth were kept in distilled water for 1 week at 37°C. Prior to the staining procedure, the original tooth colors were determined on the mid-cervical part of the buccal crown surfaces, using a reliable method for visual tooth color quantification (chapter I.3.).

The colors were expressed in 3 color dimensions: Hue, Value, and Chroma (Munsell 1961). Hue or shade is the quality of color described by the words yellow, red, green, etc. Value or brightness is the degree of grey, varying between black and white. The term Chroma indicates intensity or saturation of the color (figure 1 chapter II.4.). All color evaluations were performed by 2 independent observers. In case of disagreement the color was re-assessed. For statistical analysis of the color differences, a t-test for correlated data was used.

The pulp cavities were dried using paper points and the following endodontic sealers were introduced through the apical access into the teeth: Zinc-oxide Eugenol cement (Kraepalien & Holin, Bussum, The Netherlands), Grossman's non-staining cement (Standard Dental Products, 's Gravenhage, The Netherlands), AH26 (silver containing; De Trey Dentsply, Zurich, Switzerland), Diaket (Espe GMBH, Seefelt, BRD), N2 universal (Indrag AGSA, Losone, Switzerland), Riebler's paste (Wera Karl, Bissingen, BDR), Endomethasone (Septodont, Paris, France), and Tubli-Seal (Sybron Kerr, Michigan, USA). The sealers were prepared as prescribed by the manufacturers. Each sealer was introduced into the pulp cavities of 3 teeth. Three control teeth were filled in distilled water.

A ligature wire was fixed around the cervix of the teeth and the teeth were hung root-upwards in a test tube containing distilled water (figure 2 chapter II.3.). To control the moisture content in the enamel, the coronal portions were immersed in water. The bottles were closed with a cap, to which the wire was attached. The samples were coded and incubated at 37°C for 7 weeks. Then the color of the external buccal surfaces was again determined. Next, the internal staining patterns of the teeth were investigated.

Examination of internal staining patterns

Using a diamond separating disc (Horico, Berlin, BDR) the teeth were hemi-sectioned along the long axis in a bucco-lingual direction. The cut surfaces of the mesial parts were polished with abrasive paper (Carborundum no. 500, Dusseldorf, BDR) and water. Remnants of endodontic sealer were removed. The polished surfaces were examined with the naked eye under standard lighting conditions (Philips TL 47, Eindhoven, The Netherlands) for transmitted light, using the control teeth as reference. The staining patterns were evaluated for 2 separate criteria: a percent coverage-score and an intensity-score (Schemehorn 1982). The scoring criteria are outlined in table 1. Each section was evaluated 3 times by 2 independent observers. The inter-observer agreement was assessed using Cohen's 'kappa' (Cohen 1960); the inter-observer association by using a χ^2 test. During the entire procedure, dehydration of the tooth structure was prevented.

For each group of materials, 1 bucco-lingual slide section was prepared from a remaining distal part. Rough sections were prepared using a separating disc, which were further ground by hand on a whetstone to a thickness of about 80 μm. The slides were mounted in synthetic resin (Eukitt Kindlerr, Freiburg, BDR) and examined under a light microscope (Leitz, Wetzlar, BDR; 40-400X) to look for further details.

TABLE 1:
Grading criteria for dentin discoloration

PERCENT COVERAGE SCORES	INTENSITY SCORES
0: No observable stain	
	1: Light stain
1: Stain up to 1/3 of the dentin layer	
	2: Moderate stain
2: Stain between 1/3 and 2/3 of the dentin layer	
	3: Heavy stain
3: Stain on more than 2/3 of the dentin layer	

II.6.4. RESULTS

The original tooth colors and the tooth colors 7 weeks after introduction of the sealers into the tooth crowns, are presented in table 2. The following discolorations patterns were observed on the external buccal tooth surfaces: (1) Grossman's cement, Zinc-oxide Eugenol, Endomethasone, and N2 induced a moderate orange-red stain. (2) Diaket and Tubli-Seal caused a mild pink tooth discoloration. (3) AH26 gave a distinct color shift towards grey. (4) Riebler caused a severe dark red stain. (5) During the examination period, no discoloration could be demonstrated for the control teeth.

Table 3 gives the intensity-scores and percent coverage-scores, of the intrinsic staining patterns in the discolored teeth. The following discoloration patterns were observed inside the teeth: (1) In the tooth crowns filled with Tubli-Seal, Diaket, and AH26 a light stain was visible to a depth of 1/3 of the dentin. (2) For Grossman's cement, Zinc-oxide Eugenol, Endomethasone, and N2 a moderate dentinal stain was recorded, which penetrated to a minimum of half way into the dentin. (3) The entire dentin of the teeth filled with Riebler's paste, was severely discolored.

Neither for the intensity-score nor for the percent coverage-score, could significant differences between observers be demonstrated (Kappa: $p < 0.01$; χ^2: $p < 0.01$).

A pronounced, yellowish-brown translucent band at the dentino-enamel junction, was observed in the sections of teeth filled with Zinc-oxide Eugenol, Grossman's cement, Endomethasone, and N2.

In the thin slide sections of teeth filled with Riebler's paste, the cementum was stained intensely red. The thin slide sections did not reveal further details on the internal staining patterns; in most cases the stained area was hardly detectable.

II.6.5. DISCUSSION

Schemehorn (1982) designed a method for scoring stain accumulation on external buccal tooth surfaces. He defined separate stain grading criteria for the amount of the tooth surface covered with stain and for the intensity of the stain. The same method was used in this study for scoring the internal discoloration in hemi-sections of teeth, discolored by endodontic materials. For this purpose, the scoring criteria were slightly altered (table 1).

TABLE 3:
Mean intensity-scores and percent coverage-scores (± standard deviations) of the internal staining patterns in teeth, discolored during 7 weeks with endodontic sealers. For each sealer 3 teeth were examined three times by two observers (N = 18).

	INTENSITY (N = 18)	PERCENT COVERAGE (N = 18)
Grossman's cement	1.28 ± 0.46	1.78 ± 0.55
Zinc-oxide Eugenol	1.39 ± 0.50	2.00 ± 0.34
Tubli-Seal	1.06 ± 0.42	1.22 ± 0.55
Diaket	0.94 ± 0.54	0.89 ± 0.47
AH26	0.94 ± 0.42	0.94 ± 0.42
Endomethasone	1.89 ± 0.47	2.33 ± 0.49
N2	1.94 ± 0.42	2.06 ± 0.54
Riebler's paste	3.00 ± 0.00	3.00 ± 0.00

Tables 2 and 3 indicate that for each material the degree of internal discoloration corresponds to the degree of external discoloration. For all experimentally discolored teeth, the dentin was partly to entirely stained. This is probably caused by penetration of staining components from the filling materials into the dentin. No discoloration could be demonstrated in the enamel. Since humid enamel is highly translucent, the stained dentin is visible on the external tooth surfaces.

In view of the internal staining patterns, some remarks can be made concerning the therapy and prevention of discolorations induced by endodontic sealers. For internal bleaching of discolored pulpless teeth, it is often recommended to eliminate as much stained dentin as possible (Ingle 1976). According to the results of this study, a considerable part of the dentin is stained in teeth discolored by endodontic sealers. Elimination of the stained dentin will, therefore, result in an undesirable weakening of the crown. In addition, sufficient dentin should remain in case ,at a later date, a full crown preparation is indicated (Cohen 1980). Preferably, the permeability of the dentin for the bleaching agents should be increased, which is accomplished by acid-etching the wall of the pulp chamber (Pashly 1978).

By sealing the dentinal tubuli, a varnish layer could act as a barrier to the diffusion of staining substances into the dentin. Such treatment might be valuable in preventing tooth discoloration due to endodontic sealers. A number of materials is suggested to seal the pulp cavity after bleaching, in order to minimize re-discoloration or maintain translucency (Grossman 1981). These suggestions are based mainly on empirirism (Cohen 1980). The efficiency of various materials to prevent discoloration, should be investigated in-vitro.

TABLE 2:
Mean color-scores on the external buccal tooth surfaces (N = 3; ± standard deviation) before and 7 weeks after introduction of the endodontic sealers.

	HUE		VALUE		CHROMA	
	original	7 weeks	original	7 weeks	original	7 weeks
Control	1.02 ±0.00	1.01 ±0.03	71.6 ±1.1	70.9 ±1.3	0.56 ±0.02	0.54 ±0.03
Grossman's cement	1.01 ±0.04	0.91 ±0.02*	69.1 ±4.7	70.5 ±4.8	0.61 ±0.08	0.59 ±0.15
Zinc-oxide Eugenol	0.99 ±0.02	0.85 ±0.02*	70.5 ±1.9	69.5 ±2.1	0.60 ±0.04	0.61 ±0.16
Tubli-Seal	0.98 ±0.02	0.94 ±0.05	67.1 ±1.1	67.1 ±1.8	0.62 ±0.04	0.64 ±0.12
Diaket	0.96 ±0.02	0.93 ±0.03	68.6 ±3.7	65.3 ±0.4	0.61 ±0.12	0.67 ±0.10
AH26	1.01 ±0.03	1.00 ±0.04	69.8 ±1.6	64.0 ±2.0**	0.59 ±0.01	0.56 ±0.04
Endomethasone	0.99 ±0.02	0.87 ±0.03**	71.4 ±2.5	67.1 ±1.1*	0.60 ±0.04	0.63 ±0.06
N2	1.00 ±0.04	0.89 ±0.04**	70.8 ±4.0	69.7 ±2.9	0.62 ±0.08	0.54 ±0.08
Riebler's paste	0.96 ±0.03	0.65 ±0.05**	70.2 ±2.8	57.8 ±2.7**	0.60 ±0.06	0.71 ±0.02*

Score before > after : Hue = more orange-red ; Value = darker ; Chroma = less intense.
Score after > before : Hue = more yellow-green; Value = brighter; Chroma = intenser.
* significant difference compared to original tooth color (*$p < 0.05$; **$p < 0.01$).

A characteristic yellowish-brown band, was observed on the amelo-dentinal border of teeth filled with Zinc-oxide Eugenol, Grossman's cement, Endomethasone, and N2. The liquid part of these materials consists almost exclusively of Eugenol. Hume (1984) demonstrated that fresh Zinc-oxide Eugenol mixtures release Eugenol, which continues after setting at a lower rate. He further demonstrated that Eugenol penetrates through a layer of dentin. At the amelo-dentinal junction, the dentinal tubuli spread out a mass of branches, forming an area that is almost entirely organic. Since organic tissue decomposes upon devitalisation, a large free space may be present between the dentin and the enamel in extracted teeth. Perhaps the band at the amelo-dentinal junction, observed in the sectioned teeth, was formed by Eugenol accumulation.

Albers (1977) demonstrated that N2 components can diffuse through a layer of dentin, causing irritation of soft tissues. The cementum of teeth discolored with Riebler's paste, was intensely stained. This indicates that staining components of Riebler, pass through the dentin and cementum. Perhaps these components cause damage to the periodontal tissue.

BLEACHING OF TOOTH DISCOLORATION CAUSED BY ENDODONTIC SEALERS[1]

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II.7.1. ABSTRACT

This in-vitro study, evaluated the bleaching of teeth discolored by endodontic sealers. Extracted premolars were stained from within using Grossman's cement, Zinc-oxide Eugenol, Tubli-Seal, AH26, Endomethasone, N2, or Riebler's paste. The color of the external buccal tooth surfaces was assessed before and 6 months after the introduction of the sealers. Each sealer caused measurable discoloration of tooth crowns. After removal of the sealers, the stained teeth were bleached for 2 weeks using a 'walking bleach' technique. Six months after bleaching, the color stability of the bleached teeth was evaluated. For all teeth, a distinct change to a lighter color was noted after bleaching. Some re-discoloration was observed in each group of teeth 6 months after bleaching.

II.7.2. INTRODUCTION

Crown discoloration following root canal therapy, is a common problem when endodontic filling materials, organic debris, or both are left in the pulp chamber. A discolored anterior tooth can present a serious esthetic problem for a patient. In such cases, internal bleaching can be attempted to restore the normal tooth color.

Bleaching has several advantages over crowning (Howell 1980). First, only a limited amount of dental tissue is lost. Second, gingival irritation is avoided. In addition, bleaching is economically an attractive solution.

During the bleaching procedure, a strong oxidizing agent is introduced into the pulp chamber to convert the stained substances into colorless products. The principle causes of tooth discoloration related to endodontic treatment are: decomposition of pulp remnants, hemorrhage into the pulp chamber, and the use of discoloring drugs and filling materials. It is generally accepted that discolorations caused by dental materials are difficult to eliminate by bleaching, using the bleaching products that are currently available (Nicholls 1977). The prognosis is good for bleaching teeth discolored by necrotic pulp tissue or blood components (Cohen 1984). Some color regression is often reported after an initial perod of bleaching succes (Brown 1965; Howell 1981).

In a recent study, tooth discolorations were created experimentally, using root canal sealers (chapter II.4.). The sealers were placed into the pulp cavities of extracted human premolars. Within several weeks, color changes were measurable on the buccal surfaces of the teeth. The aim of the present study was to assess the extent of color change obtained by internally bleaching of teeth, discolored by endodontic sealers. In addition, the color stability of the bleached teeth was evaluated over the medium term.

II.7.3. MATERIALS AND METHODS

Preparation of the discolored teeth

Sound human premolars, extracted for orthodontic purposes, were used. The teeth were stored in tap water at 4°C immediately after extraction.

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After cleaning and polishing the external surfaces, the apical segment of the roots was removed. The pulps were extirpated and the pulp chambers instrumented through an apical access opening (chapter II.3.). The pulp chambers were then irrigated successively with EDTA and NaOCl (Goldman 1982). After irrigation the teeth were kept in distilled water for 1 week at 37°C. The original tooth colors were assessed prior to the staining procedure.

A reliable method for visually determining tooth color, was used to evaluate the colors of the buccal surfaces of the teeth (chapter I.3.). The tooth colors were expressed in 3 visual color dimensions: Hue, Value, and Chroma (Munsell 1961). Hue or shade is that quality of color which is described by such words as yellow, red, or green. Value or brightness is the degree of grey. The term Chroma indicates intensity or saturation (figure 1 chapter II.4). All color evaluations were performed by 2 independent observers, whose color vision was found to be normal by the 100 Hue Farnsworth-Munsell test. If the observers disagreed, the color was re-assessed. For statistical analysis of the differences in tooth color, a t-test for correlated data was used.

The pulp cavities were dried using paper points and the following endodontic sealers were introduced into the teeth: Zinc-oxide Eugenol cement (Kraepalien & Holin, Bussum, The Netherlands), AH26 (De Trey Dentsply, Zurich, Switzerland), Grossman's non-staining cement (Standard Dental Products, 's Gravenhage, The Netherlands), N2 universal (Indrag AGSA, Losone, Switzerland), Riebler's paste (Wera Karl, Bissingen, BDR), Endomethasone (Septodont, Paris, France), and Tubli-Seal (Sybron Kerr, Michigan, USA). The sealers were prepared as prescribed by the manufacturers. Each sealer was introduced into the pulp cavities of 3 teeth. Three control teeth were filled with distilled water.

A ligature wire was fixed around the cervix of the teeth and the teeth were suspended, with the root upwards, in a test tube containing water. To keep the enamel hydrated, the crowns were immersed in water. The bottles were closed with a cap, to which the wire was attached. The samples were coded and incubated at 37°C. The tooth colors were determined after 6 months.

Bleaching of teeth

After 6 months of incubation, the endodontic sealers were removed from the pulp chambers with suitable hand instruments. To remove all remnants of sealer, the pulpal walls were prepared with a low speed round bur. Then an additional color reading was performed.

A drop of 35% phosphoric acid was placed in each pulp chamber for 1 minute. The acid was removed by rinsing the chamber with a large volume of water. Cotton pellets, saturated chloroform and then 96% ethanol, were used to wash the pulpal walls. After evaporation of the ethanol, the pulp cavities were completely filled with a thick slurry of sodium-perborate powder in 30% H_2O_2. The apical access preparations were double sealed with Cavit (Espe GMBH, Seefelt, BDR) and IRM (Caulk Dentsply, Milford, USA). During the bleaching procedure, the teeth were incubated at 37°C as described for the staining of teeth.

After 1 week, the tooth colors were evaluated. Then the bleaching agents were replaced by a fresh mixture. The access preparations were sealed and the teeth were incubated for another week. Two weeks after starting the bleaching procedure and before thoroughly flushing the pulp chamber with water, a second color determination was made. Then the chambers were dried and filled with Consice (3M, St Paul, USA). The teeth were incubated again at 37°C. After 6 months, the color stability of the bleached teeth was assessed.

II.7.4. RESULTS

The color readings obtained 6 months after introduction of the sealers, were not influenced by the presence or absence of the sealers in the pulp cavity.

The original tooth colors, the colors 6 months after introduction of the sealers, as well as the colors after a bleaching procedure of 2 weeks are presented in table 1. The range of standard deviations was 0.00-0.08 for Hue, 0.2-6.6 for Value, and 0.01-0.12 for Chroma. In a descriptive way, the following discoloration patterns were observed: (1) The color of the control teeth was stable during the staining period of 6 months. After bleaching, the tooth colors became a very light and pale yellowish-green color. Six months after bleaching, the teeth became slightly darker but still remained lighter than the original color. (2) Grossman's cement, Zinc-oxide Eugenol cement, Tubli-Seal, and N2 induced a light to moderate orange-red tooth discoloration. As a result of the bleaching procedure, the teeth became more yellowish-green, lighter and less saturated compared to the original tooth color. The Value-score, observed 6 months after bleaching, was similar to the pre-stain Value-score. (3) Endomethasone produced a moderate red stain, which changed in a mild yellowish-green color after bleaching. Within half a year, the Hue-score was almost equal to the original Hue-score again, whereas the Value became slightly lower. (4) AH26 caused a distinct color shift towards grey, which completely disappeared after bleaching but tended to recur afterwards. The Hue-score increased following the bleaching procedure and remained at a higher level. (5) For the teeth filled with Riebler's paste, a severe dark red stain was recorded. The colors improved upon bleaching, although the original color was not reached. At subsequent color readings the discoloration got worse.

In all cases, a bleaching period of 2 weeks was more effective than a bleaching period of 1 week.

II.7.5. DISCUSSION

Freccia (1982) stained extracted teeth with blood and compared the results of 3 non-vital bleaching techniques: a thermo-catalytic, a 'walking bleach' (Nutting 1967), and a combination technique. The techniques were equally effective in bleaching blood-stained teeth, whereas the walking bleach technique used least operator time. For this reason, the walking bleach technique was selected for the present study.

Extracted human premolars were stained during 6 months using a number of endodontic sealers. Before the bleaching procedure was started, the tooth colors were assessed. Then the sealers were removed from the pulp cavities and the tooth colors were re-assessed. Similar tooth colors were found before and after removal of the sealers. Apparently, the discoloration was not due to the presence of colored material in the pulp chamber, showing through the dentin and the enamel. It is more likely that the stain penetrated into the dentin, as confirmed earlier (chapter II.6.).

Before bleaching, the sealers were removed from the pulp cavities by mechanical means. To avoid weakening of the tooth crowns, no efforts were made to eliminate the stained dentin. Mechanical preparation of pulp cavities results in the deposition of dentinal debris on pulpal walls, the so-called 'smeared layer' (McComb 1975). A smeared layer possibly interferes with the permeability of the dentin for bleaching agents. This layer was removed by acid-etching (Pashly 1978), to provide optimal diffusion of the bleaching agents into the dentin. Subsequently, the dentin was swabbed

TABLE 1:
Average Hue, Value, and Chroma-scores (N = 3) of the original tooth colors, the tooth colors 6 months after introduction of the sealers, and the tooth colors after a bleaching period of 2 weeks.

	Control	Grossman's cement	Zinc-oxide eugenol	Tubli-Seal	AH26	Endometha-sone	N2	Riebler's paste
				HUE				
original	1.03	1.00	1.00	0.98	0.96	0.96	1.00	0.91
6 months stain	1.02	0.93**	0.88**	0.93*	0.97	0.86**	0.95*	0.55**
2 weeks bleach	1.16*	1.11	1.13*	1.13*	1.12**	1.02*	1.14*	0.77**
				VALUE				
original	71.6	70.8	72.0	69.2	72.3	70.1	70.8	70.8
6 months stain	70.9	69.3	69.1*	69.8	67.4**	67.8*	68.3*	57.7**
2 weeks bleach	76.6*	75.5	77.0	77.0*	75.7	70.8	73.8	69.4*
				CHROMA				
original	0.56	0.56	0.53	0.59	0.54	0.59	0.56	0.55
6 months stain	0.54	0.52	0.55	0.54	0.55	0.54	0.61	0.66*
2 weeks bleach	0.45	0.45*	0.47*	0.47*	0.46*	0.53	0.45	0.50

Score before > after: Hue = more orange-red; Value = darker; Chroma = less intense
Score after > before: Hue = more yellow-green; Value = brighter; Chroma = intenser
* significant color difference compared to the original tooth color (* $p < 0.05$; ** $p < 0.01$)

with chloroform, to dissolve fatty substances which may act as a barrier to the diffusion of hydrogen-peroxide. The final step was the dehydration of the dentin with ethanol (Nicholls 1977).

In bleaching studies on patients having discolored root-filled teeth, it is difficult identify the etiology of discoloration. Failure of the bleaching procedure was blamed on staining by dental materials (Brown 1965), therefore, the prognosis for bleaching discolorations due to dental materials was usually said to be poor. In the present study, controlled tooth discoloration was produced in-vitro, using 7 endodontic sealers. All discolorations responded to the bleaching procedure. The high percentage of success was possibly due to several factors. First, bleaching is more likely to be succesful in recently stained teeth than in teeth with long standing discolorations (Brown 1965). The discoloration created in the teeth used for this study, only existed for half a year. Older discolorations probably would been more difficult to bleach. Second, young teeth bleach faster than old teeth because the dentinal tubules are wider. The premolars used for this study, were obtained from young patients. Third, the measures taken improve the diffusion of bleaching agents into the dentin might have been very effective.

In this in-vitro study, the color of each stained tooth improved markedly upon bleaching. For most experimental teeth and the control teeth, the colors recorded after bleaching were lighter and paler than the original tooth colors. In the mouth of a patient, usually adjacent (unstained) teeth are present. It is difficult to conclude from this laboratory study, whether the results obtained will be satisfactory in clinical situations.

It has been reported that discoloration can recur after successful bleaching. Recurrance of the discoloration could be caused by external or internal factors, or by a combination of both (Howell 1981). External re-discoloration results from penetration of pigmented substances from the oral environment into the dentin, for example, due to leaking restorations. In addition, the porosity of the enamel may be increased in pulpless teeth (Pearson 1958). The teeth possibly dehydrate during the bleaching procedure, due to the use of alcohol or rubberdam isolation. Since desiccated teeth appear to be lighter, internal re-discoloration may result from rehydration after bleaching. Furthermore, the colorless products produced by bleaching, may be unstable and return to a colored state. In this study, the external factors were excluded since the teeth were only in contact with distilled water. Nevertheless, each group of teeth showed some color change after bleaching, indicating that internal factors were involved. Six months after bleaching, all teeth were somewhat darker than immediately after bleaching, which could partly be explained by rehydration. The decompositon of bleaching products may also play a role, because different degrees of re-discoloration were observed between stained and control teeth, and also between teeth discolored by different materials.

In view of the recurrance of the discoloration, the pulp cavity should not be varnished after bleaching as long as the cause of re-discoloration is uncertain. The phenomenon of re-discoloration, therefore, needs to be investigated further.

II.7.6. SUMMARY AND CONCLUSIONS

Extracted premolars were stained from within, using 7 root canal sealers. After 6 months of incubation, measurable coronal tooth discoloration was recorded for each sealer. Then, the stained teeth were internally bleached

for 2 weeks using a 'walking bleach' technique. The appearence of the stained teeth improved markedly upon bleaching. Six months after the bleaching procedure, some color regression was observed for each group of teeth. The problem of re-discoloration should be further investigated. The results obtained from this laboratory study, should be verified in a clinical experiment.

DISCUSSION AND CONCLUSIONS

II.8.1. DISCUSSION

In designing an in-vitro technique to induce intrinsic tooth discoloration, the conditions formulated in chapter II.1. were fulfilled. These conditions concerned the clinical relevance and the reproducibility of the discoloration and the humidity control of the teeth.

Three arguments can be adduced in support of the clinical relevance of the experimentally induced tooth discoloration (chapter II.3.). First, the discoloration is clinically relevant in the way the materials were brought into contact with the teeth. The material to be investigated, was introduced into the pulp chambers of experimental teeth. The interaction between the staining agents and dental tissue, therefore, is comparable to the discoloration process occurring after endodontic therapy. Furthermore, the technique can be applied to examine the staining potentials of a variety of dental materials; liquid as well as solid. Second, the location on the teeth where the color determinations were performed, is also clinically relevant. Intrinsic discolorations showing through the enamel of tooth crowns, are of clinical interest. For this reason, the coronal color changes were assessed on the external buccal tooth surfaces. Third, the selection of a hemoglobin solution for the development of the in-vitro technique, is clinically relevant. Hemoglobin or its decomposition products cause tooth discoloration after trauma (Grossman 1981; Cohen 1984). The course of experimental discoloration resembled post-traumatic tooth discoloration (Jacobsen 1980).

The technique results in reproducible discoloration of teeth. The discoloration process is likely to be influenced by the diameter and accessability of the dentinal tubuli. In view of the reproducibility (and availability), premolars were used for the experiments, although stained anterior teeth are clinically more striking. The premolars, extracted for orthodontic purposes, were expected to have about the same developmental stage implicating the diameter of the dentinal tubuli to be similar (Nalbandian 1960). Furthermore, the pulpal wall of the teeth was prepared to remove the 'smeared layer' covering the entrance of the tubuli (McComb 1975). This treatment results in optimal diffusion of staining substances into the dentin, which will benefit the reproducibility of the discoloration process.

The moisture content of the teeth is maintained succesfully using water immersion for humidity control. The technique, therefore, allows for long-term studies on tooth discoloration without dehydration of the enamel disturbing the color evaluations.

Since the technique for discoloration turned out to be satisfactory, it was applied for a number of investigations (chapters II.4 - II.7). This sequence of studies provided some interesting information on intrinsic discoloration related to dental materials.

It enabled a comparative study of discoloration effects of endodontic sealers, temporary and permanent filling materials, cements and cavity liners (chapters II.4. and II.5.). Each of the 8 root canal sealers examined, induced tooth discoloration to some extent (chapter II.4.). To prevent discoloration after endodontic therapy, remnants of sealer should always carefully be eliminated out of the pulp chamber and the root canal 2 mm below the level of the crown. It is further suggested to select a sealer, which is allocated in the least staining category. A number of the temporary filling materials, cements, and cavity liners appeared to be non-staining (chapter II.5.). The single permanent filling material

investigated, showed no discoloration. In future studies the staining properties of other permanent filling materials should be examined.

For all teeth discolored by endodontic sealers, hemi-sectioning showed that a considerable part of the dentin was stained (chapter II.6.). Thus, to prevent intrinsic discoloration, the diffusion of staining substances into the dentin should be blocked. This can be accomplished using a suitable varnish solution before obturating the canal. With respect to the therapy of intrinsic discoloration, it is often advised to remove the stained dentin before bleaching (Ingle 1976). To avoid weakening of the tooth crown, the stained dentin should better be saved. In stead, acid-etching should be applied to increase the permeability of the dentin for bleaching agents (Pashly 1978).

The appearence of the teeth, stained by endodontic sealers, improved markedly upon bleaching using current agents (chapter II.7.). This result was rather unexpected, since in most endodontic textbooks it is stated that discolorations due to dental materials are difficult to bleach (Nicholls 1977). Because bleaching has several advantages over crowning, it is concluded that it is worth trying to bleach teeth which are stained by dental materials.

Evidently, all results mentioned above were obtained from in-vitro studies, implicating that the same does not necessarally hold for in-vivo situations. Non-vital teeth, however, are devoid of blood and nerve supply. In view of this, it might be expected that the susceptability for intrinsic staining is quite similar for non-vital and extracted teeth.

Further applications of the technique to create intrinsically discolored teeth, include research on the effectivity of varnish solutions to block penetration of staining substances into the dentinal tubuli. Also, the development of non-staining materials without sacrificing other valuable properties, can be quantitatively assessed. Using the technique, the modified version of the material could be examined in-vitro.

II.8.2. CONCLUSIONS

1. The in-vitro technique for producing intrinsic tooth discoloration, is reproducible and clinically relevant. The humidity content of the teeth is controlled succesfully.

2. Each root canal sealer examined in-vitro, induces tooth discoloration to some extent.

3. From the teeth experimentally discolored by endodontic sealers, a considerable part of the dentin is stained.

4. The appearence of teeth, experimentally stained by endodontic sealers, improves markedly upon internal bleaching using current agents.

5. An in-vitro study on permanent and temporary filling materials, cements, and cavity liners, revealed a number of non-staining materials.

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SUMMARY

Discoloration of tooth crowns is a common feature after root canal therapy. Such discolorations possibly result from the use of discoloring materials during dental treatment. To prevent tooth discoloration due to dental materials, reliable information is required on the staining potential of these materials. However, hardly any research has been conducted in this area. The aim of the present investigation was to assess the degree of tooth discoloration as provoced by various dental materials. For this purpose, 2 important questions had to be answered. First, is it possible to quantify the color of a tooth? Second, which technique should be employed to create reproducible tooth discoloration in-vitro? The first question gave rise to an extensive optical study. This thesis, therefore, is devided into 2 seperate parts. The investigations on tooth color determination are discussed in part I. Part II deals with tooth discoloration related to endodontic therapy.

In chapter I.1. a general theoretical discussion on the phenomenon of color is described. The optical processes playing a role in color perception are explained as well as the main methods for color determination. Then attention is payed to the specific optical phenomena that may occur during color determination on translucent dental tissues. Based on this knowledge, it is concluded that the measurement of tooth color is a complicated matter, where mistakes can easily be made. In paragraph I.1.5., a number of criteria is defined, which are applicable to a proper method for tooth color determination.

A series of color measurements on translucent materials demonstrates in chapter I.2. that, using traditional methods for color measurement on small objects such as tooth structures, doubtfull results will be obtained. Thus, the problems concerning tooth color measurement as mentioned in chapter I.1., are confirmed experimentally.

Chapter I.3. presents a new method to quantify the color of teeth. This method, characterized by visual comparison of tooth color with color standards, meets the criteria outlined in I.1. Essential in this context, is that the method is specifically designed to account for the optical properties of teeth. The method is suitable to be used in various research areas and may be applicable in future in clinical situations.

Based on the experiences described in I.3., a colorimeter for tooth color measurement is designed using the same color matching procedure. Both methods recently developed to evaluate the color of teeth, are compared in chapter I.4. In addition 2 conventional instruments, frequently used for tooth color determination, are included in this comparative study. The colorimeter seems to function rather satisfactory, although technical improvements are necessary. The results also show that using the conventional instruments, the optical properties of dental tissue are not properly taken into account.

In chapter II.1. the conditions are formulated for a useful technique for experimental discoloration of teeth. In chapter II.2., a short literature review on tooth discoloration is given comprising intrinsic as well as extrinsic discoloration.

Chapter II.3. introduces an in-vitro staining technique meeting the requirements listed in II.1. With this technique, the crowns of extracted premolars are discolored by diffusion of staining agents introduced in the pulp chamber. The results show that measurable and reproducible discoloration of teeth can be induced. Moreover, the experimental discoloration seems to have clinical relevancy. Using this staining technique combined with the method developed for tooth color determination (I.3.), the

staining potential of various dental materials can be investigated.

In chapter II.4., the discoloring potential of 8 root canal sealers is examined. In the experimental situation, each sealer causes significant discoloration of teeth, whereas for the individual sealers different degrees of discoloration are recorded. Chapter II.5. describes a similar study on 10 materials which are mainly applied into the coronal part of a tooth. This group of materials consists of temporary and permanent filling materials and materials used for cementation or insulation. The results indicate for each material whether and to what extent tooth discoloration is induced.

In chapter II.6., the staining patterns inside the dental hard tissues are studied in further detail. The study reveals that a considerable part of the dentin is stained in teeth discolored by root canal sealers.

Since bleaching of discolored teeth is of clinical interrest, the effectivity of internal bleaching is investigated on endodontically stained teeth. The results of chapter II.7. demonstrate that the appearance of discolored teeth markedly improved after the bleaching procedure.

SAMENVATTING

Na een wortelkanaalbehandeling wordt dikwijls een storende verkleuring van de tandkroon waargenomen. Een dergelijke verkleuring kan ondermeer voortkomen uit het gebruik van verkleurende materialen tijdens de tandheelkundige ingreep. Teneinde tandverkleuring als gevolg van tandheelkundige materialen te voorkomen, zijn betrouwbare gegevens vereist omtrent de verkleurende eigenschappen van deze materialen. Tot op heden zijn echter weinig systematische studies verricht op dit terrein. De doelstelling van het onderhavige onderzoek was de mate van tandverkleuring vast te stellen veroorzaakt door diverse tandheelkundige materialen. Hierbij deden zich een tweetal belangrijke vragen voor. Ten eerste, is het mogelijk de kleur van een tand te quantificeren? Ten tweede, op welke wijze kan reproduceerbare verkleuring van gebitselementen in-vitro worden geïnduceerd? De beantwoording van de eerste vraag bleek aanleiding te geven tot een uitvoerig optisch georiënteerd onderzoek. Derhalve zijn in dit proefschrift 2 aparte delen te onderscheiden. In deel I wordt verslag gedaan van het onderzoek betreffende het onderwerp tandkleurbepaling. Deel II handelt over tandverkleuring in relatie tot endodontische behandeling.

Hoofdstuk I.1. vangt aan met een algemene theoretische beschouwing over het begrip kleur. Hierbij komen de optische processen aan de orde welke een rol spelen bij de kleurgewaarwording, evenals de voornaamste kleurbepalingsmethoden. Vervolgens wordt ingegaan op de specifieke optische verschijnselen, die bij kleurbepalingen aan het doorschijnende tandweefsel te verwachten zijn. Op grond van het verworven inzicht wordt geconstateerd dat het meten van tandkleur een uiterst gecompliceerde aangelegenheid is, waarbij fouten snel kunnen optreden. Ter afsluiting van hoofdstuk I.1. worden een aantal criteria gedefinieerd, waaraan een geschikte methode voor tandkleurbepaling dient te voldoen.

Aan de hand van metingen aan doorschijnende materialen wordt in hoofdstuk I.2. aangetoond, dat traditionele kleurmetingen aan kleine objecten verkeerde resultaten opleveren. De veronderstelling geuit in hoofdstuk I.1., betreffende de problematiek rond tandkleurmeting, is hiermee experimenteel bevestigd.

Hoofdstuk I.3. presenteert een nieuwe methode om de kleur van gebitselementen te quantificeren. Deze methode, gekenmerkt door het visueel vergelijken van de tandkleur met kleurstandaarden, voldoet aan de criteria opgesteld in paragraaf I.1.5. Essentieel in dit verband is dat de methode is aangepast aan de optische eigenschappen van tandweefsel. De methode is geschikt voor velerlei research doeleinden en wellicht in de toekomst ook voor praktisch klinische doeleinden.

Gebaseerd op de bevindingen in hoofdstuk I.3. is een colorimeter voor tandkleurmeting ontworpen, waarbij de kleurbepalingsprocedure volgens hetzelfde principe plaatsvindt. In hoofdstuk I.4. worden beide recent ontwikkelde methoden voor tandkleurbepaling naast elkaar gezet. In deze vergelijkende studie zijn eveneens 2 conventionele instrumenten betrokken, welke regelmatig worden toegepast voor tandkleurmetingen. Alhoewel technische verbeteringen noodzakelijk zijn, lijkt de colorimeter redelijk te funktioneren. Verder blijkt uit de resultaten dat bij gebruik van de conventionele apparatuur onvoldoende rekening wordt gehouden met de optische eigenschappen van tandweefsel.

In hoofdstuk II.1. worden de voorwaarden geformuleerd voor een bruikbare techniek om gebitselementen experimenteel te verkleuren. Hoofdstuk II.2. is een beknopt literatuuroverzicht over tandverkleuring, waarin zowel de intrinsieke als de extrinsieke verkleuringen worden

behandeld.

Hoofdstuk II.3. introduceert een in-vitro techniek voor intrinsieke tandverkleuring, welke tegemoet komt aan de in II.1. gestelde eisen. Met deze techniek worden de kronen van geëxtraheerde premolaren verkleurd vanuit de pulpakamer. Uit de resultaten blijkt dat op deze wijze reproduceerbare en meetbare verkleuring van tandkronen wordt gecreëerd, bovendien blijkt de experimentele verkleuring klinisch relevant te zijn. Met behulp van de verkleuringstechniek in combinatie met de methode ontwikkeld voor tandkleurbepaling (I.3.) is het mogelijk systematisch onderzoek te doen naar de verkleurende eigenschappen van diverse materialen.

Hoofdstuk II.4. beschrijft het onderzoek naar de verkleurende eigenschappen van 8 wortelkanaalcementen. In de gekozen experimentele opstelling blijkt ieder cement significante tandverkleuring tot gevolg te hebben; er blijken echter duidelijke verschillen te bestaan in de mate waarin de materialen verkleuring teweeg brengen. Hierop aansluitend is een soortgelijke studie uitgevoerd met 10 materialen die voornamelijk in de tandkroon worden aangebracht (hoofdstuk II.5.). Tot deze groep materialen behoren ondermeer temporaire en permanente vulmateralen en materialen voor cementatie of isolatie. Uitgaande van de resultaten kan voor elk materiaal worden aangegeven of het al dan niet verkleuring van het tandweefsel veroorzaakt.

In hoofdstuk II.6. worden de verkleuringspatronen binnenin het harde tandweefsel nader bestudeerd. Uit deze studie komt naar voren dat bij tanden, verkleurd door wortelkanaalcementen, steeds een aanzienlijk gedeelte van het dentine verkleurd is.

Omdat in de kliniek het ontkleuren van verkleurde elementen van belang is, wordt deel II afgerond met een onderzoek naar het effect van intern bleken van elementen verkleurd door wortelkanaalcementen. De resultaten van hoofdstuk II.7. laten zien dat na het bleken het uiterlijk van alle verkleurde tanden aanzienlijk verbeterd is.

CURRICULUM VITAE

De schrijfster van dit proefschrift werd 12 april 1958 geboren te Naarden. De middelbare school werd in Bilthoven doorlopen en in 1976 afgerond met het Atheneum-B diploma. In hetzelfde jaar begon zij met de studie Tandheelkunde te Utrecht. Na het behalen van het Kandidaatsexamen in 1978 (met lof) en het Doctoraal I examen in 1979 (met genoegen), is zij van studierichting veranderd. In het kader van het Doctoraalexamen Geneeskunde vrije studierichting, heeft zij gedurende 2 jaar (1980-1982) geparticipeerd aan het onderzoek betreffende immunisatie tegen tandcaries (o.l.v. Drs. E.M. Kamp). Dit onderzoek werd grotendeels verricht bij de vakgroep Preventieve Tandheelkunde te Utrecht (hoofd: Prof.Dr. O. Backer Dirks). Deelprojecten zijn uitgevoerd bij de afdeling Medische Histologie (hoofd: Prof.Dr. H. van der Donk) en de afdeling Biochemie van de Mondholte (hoofd: Prof.Dr. G.J.M.Th. Tonino) beide te Utrecht. Sinds 1982 is zij als wetenschappelijk medewerker verbonden aan de afdeling Conserverende Tandheelkunde voor Volwassenen te Nijmegen (Prof.Dr. A.J.M. Plasschaert), alwaar het hiervoor beschreven promotie onderzoek werd verricht.

STELLINGEN

1. Knaagdieren zijn ongeschikt als proefdiermodel voor bestudering van de rol van speeksel-antilichamen op het ontstaan van cariës.

2. De thermische isolatie van onderlagen op basis van calcium hydroxide wordt overschat. (Spierings: J Dent Res, 1985)

3. Non-directieve gezondsheidsvoorlichting kan weliswaar leiden tot een daadwerkelijke zelfzorg door de patiënt, doch kan afwijken van de door de professie wenselijk geachte gedragslijn. (Schut: World Conf Health Educ, 1985)

4. De formules voor het schatten van de hoeveelheid lichaamsvet bij meisjes dienen gecorrigeerd te worden voor het biologische ontwikkelingsstadium. (Biersteker, Proc XIII Int Conf Nutrition, 1985)

5. Een goede mondhygiëne zal de werking van systemische vaccinatie met Streptococcus mutans verminderen.

6. Het verdient aanbeveling de kleurring die gebruikt wordt bij kleurbepaling voor composiet restauraties, niet uit kunsthars maar uit composiet te vervaardigen.

7. Nog steeds zijn er wetenschappers die 'significant' gelijk stellen met 'relevant'.

8. Tandverkleuring na endodontische behandeling kan grotendeels voorkomen worden door een juist gebruik van de geschikte materialen. (dit proefschrift)

9. Vanwege de opbouw, de vorm, het formaat en de localisatie van gebitselementen, is de objectivering van tandkleur uiterst gecompliceerd. (dit proefschrift)

10. Het krachtdadige bezuigingsbeleid heeft bij de universiteiten in ons land geleid tot aanzienlijke besparingen in de schoonmaakkosten.

11. Als men de wervingskracht van de KUN een belangrijk beleidscriterium vindt, dan dient men te overwegen openings- en slotgebed tijdens promotieplechtigheden facultatief te stellen.

12. Baghwan's gevangenneming zal leiden tot arbeidstijdverkorting bij Rolls Royce.

13. Everything should be made as simple as possible, but not simpler. (Albert Einstein)

14. Men heeft nooit een tweede kans voor een goede eerste indruk.

Stellingen behorend bij het proefschrift:
Tooth color and tooth discoloration.
Tina van der Burgt, 20 december 1985.