Journal of Dentistry (2004) **32**, 3–12

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Journal of Dentistry

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Tooth colour: a review of the literature

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Received 4 September 2003; revised 14 October 2003; accepted 15 October 2003

KEYWORDS
Tooth whitening; Tooth colour; Colour measurement; Colourimeter; Tooth bleaching; Colour perception; Peroxide; aesthetics

Summary *Objectives*. To review current knowledge with respect to tooth colour and its measurement.

Methods. 'Medline' database for the period 1966 to the present day and 'ISI Web of Science' database for the period 1974 to the present day were searched electronically with key words tooth, teeth, colour and color.

Conclusions. The colour and appearance of teeth is a complex phenomenon, with many factors such as lighting conditions, translucency, opacity, light scattering, gloss and the human eye and brain influencing the overall perception of tooth colour. The measurement of tooth colour is possible via a number of methods including visual assessment with shade guides, spectrophotometry, colourimetry and computer analysis of digital images. These methods have successfully been used to measure longitudinal tooth colour changes when the dentition has undergone tooth whitening procedures.

Introduction

A smile has been said to be one of the most important interactive communication skills of a person.[1] The ultimate objective of aesthetics in dentistry is to create a beautiful smile, with teeth of pleasing inherent proportions to one another, and a pleasing tooth arrangement in harmony with the gingiva, lips and face of the patient.[2] In addition, the aesthetics of any restoration needs to consider the parameters of surface form, translucency and colour.[2-5] Patients and consumers now demand not only a healthy mouth but also a perfect smile. Indeed, it has been reported in the UK that 28% of adults are dissatisfied with the appearance of their teeth[6] and in the USA that 34% of an adult population are dissatisfied with their current tooth colour.[7]

The colour of the teeth is determined by the combined effects of intrinsic and extrinsic colourations.[8] Intrinsic tooth colour is associated with the light scattering and absorption properties of the enamel and dentine.[9] Extrinsic colour is associated with the absorption of materials (e.g. tea, red wine, chlorhexidine, iron salts) onto the surface of enamel, and in particular the pellicle coating, and which ultimately cause extrinsic stain.[10] The many factors associated with tooth discolouration and staining, both intrinsic and extrinsic, have recently been extensively reviewed.[8]

Since the extrinsic stains are on the tooth surface, these can be thoroughly removed by the abrasive action of a dental prophylaxis[11] and controlled by the regular use of an effective toothpaste.[12] There are many treatment methods and materials available to enhance the intrinsic colour of the teeth. Night guard vital bleaching, introduced in 1989 is one such technique,[13] where

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doi:10.1016/j.jdent.2003.10.013

a carbamide peroxide gel is held against the anterior teeth with a custom fitted gum shield in order to lighten the colour of the teeth. Today, tooth whitening continues to be ever more popular, either through professionally applied products[14–16] or through mass market consumer products.[17,18]

With this increase of interest in tooth whitening, this paper aims to review current knowledge with respect to tooth colour.

Colour and colour space

The phenomenon of colour is a psychophysical response to the physical interaction of light energy with an object, and the subjective experience of an individual observer.[19] Three factors can influence the perception of colour, namely, the light source, the object being viewed and the observer viewing the object. The light source can emit radiant energy of a range of wavelengths and this is characterised by the relative amount of energy emitted at each wavelength in the visible spectrum. The light source that illuminates an object affects colour perception, since individual sources contain varying quantities of each of the visible wavelengths of light. The spectral reflectance (or transmittance) of an object characterises the colour makeup of that object. The spectral reflection or transmission curve of the object represents it graphically, and provides a way of quantifying colour numerically. As objects vary in colour, so do the graphs depicting the energy being absorbed or reflected. For example, a red object looks red primarily because it reflects red wavelengths more than green and blue. The observer's visual system of eye and brain finally affects the overall perception of the colour.[20]

A major problem often arises when attempting to communicate colours to others. To this end a number of colour scales have been developed. Colour can be described according to the Munsell colour space in terms of hue, value and chroma.[21] Hue is the attribute of a colour that enables one to distinguish between different families of colour, for example, reds, blues and greens. Value indicates the lightness of a colour ranging from pure black to pure white. Chroma is the degree of colour saturation and describes the strength, intensity or vividness of a colour.

The Commission Internationale de l'Éclairage (CIE), an organisation devoted to standardisation in areas such as colour and appearance, defined in 1931 a standard light source, developed a standard observer and enabled the calculation of tristimulus values, which represent how

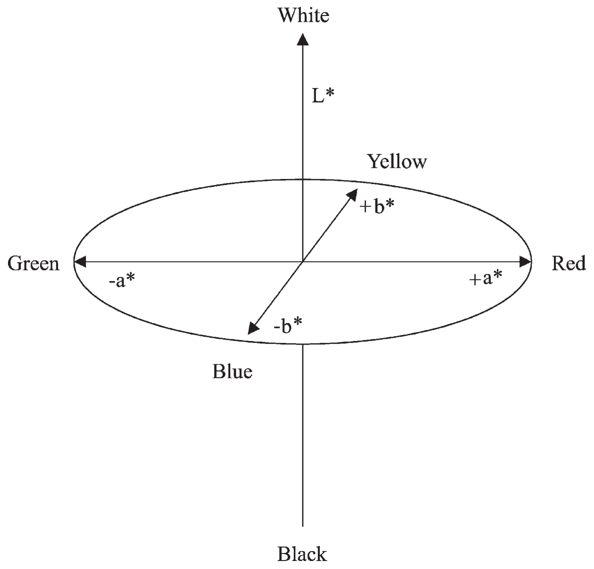

Figure 1 CIE Lab colour space.

the human visual system responds to a given colour.[21] In 1976, the CIE further defined a colour space, CIE Lab, that supports the accepted theory of colour perception based on three separate colour receptors (red, green and blue) in the eye and is currently one of the most popular colour spaces. The CIE Lab colour space represents a uniform colour space, with equal distances corresponding to equal perceived colour differences. In this three-dimensional colour space the three axes are L^*, a^* and b^* (Fig. 1). The L^* value is a measure of the lightness of an object and is quantified on a scale such that a perfect black has an L^* value of zero and a perfect reflecting diffuser an L^* value of 100. The a^* value is a measure of redness (positive a^*) or greenness (negative a^*). The b^* value is a measure of yellowness (positive b^*) or blueness (negative b*). The a^* and b^* co-ordinates approach zero for neutral colours (white, greys) and increase in magnitude for more saturated or intense colours. The advantage of the CIE Lab system is that colour differences can be expressed in units that can be related to visual perception and clinical significance.[22]

Optical properties of teeth

The colour of a tooth is determined by a combination of its optical properties. When light encounters a tooth, four phenomena associated with the interactions of the tooth with the light flux can be described:[23] (1) specular transmission of the light through the tooth, (2) specular reflection at the surface, (3) diffuse light reflection at the surface and (4) absorption and scattering of light within the dental tissues. Tooth colour has been shown to result from the volume scattering of light, i.e. illuminating light follows highly irregular light paths through the tooth before it emerges at the surface of incidence and reaches the eye of the observer.[24,25] Non-white colour is predominantly a result of absorption along these path lengths and the absorption coefficient of the tooth tissues.

Vaarkamp et al.[26] measured the light propagation through 0.85 mm thick human enamel and dentine bars. For enamel it was found that the hydroxyapatite crystals contribute significantly to light scattering, whereas for dentine the optical anisotropy observed supported the idea that tubules are the predominant cause of scattering.[27,28] The optical scattering power of enamel blocks was measured as a function of the decrease in mineral content and found that demineralisation increases the scattering coefficient by a factor of about three.[29]

Spitzer and Ten Bosch[30] measured the reflectance and transmission of thin slabs of bovine and human dental enamel at wavelengths between 220 and 700 nm. Measurements were made with a spectrophotometer and an adsorption peak at 270 nm was found in all spectra, which is outside the normal human visible light range (380–780 nm).

An in vitro study showed that the colours of 28 teeth from different patients where the enamel was removed correlated strongly with the colours of the complete tooth.[9] Thus, this study confirmed that tooth colour is determined mainly by the colour of dentine, with enamel playing only a minor role through scattering at wavelengths in the blue range. Indeed, Zijp et al.[31] reported that when thin human dental enamel slabs are observed in daylight, they appear to be pale blue in reflection and pale yellow in transmission.

A number of workers have studied the luminescence (i.e. fluorescence and phosphorescence) of dental enamel and dentine.[30,32–35] Dentine has fluorescence excitation peaks at <300, 325, 380 and 410 nm, with corresponding emission maxima at ca. 350, 400, 450 and 520 nm.[27] Enamel excitation peaks have been found at 285 and 330 nm, and emission maxima at 360 and 410 nm.[30] For bovine enamel powder an emission maxima was found at 400 nm.[35] The combination of fluorescence from dentine and enamel has been reported as enhancing the whiteness or value of teeth.[5] In contrast, Ten Bosch and Coops[9] measured the colour of tooth samples under two different light sources and concluded that under everyday lighting conditions, fluorescence does not contribute measurably to visually observed tooth colour.

Measurement of tooth colour

Many methods are currently used to assess tooth colour. These range from visual subjective comparisons using paper, coloured porcelain or acrylic resin shade guides to instrumental objective measurements using spectrophotometers, colourimeters and image analysis techniques.

Visual colour determination, by comparison of the tooth with standard colour tooth shade guides, is the most frequently applied method in dentistry.[24] It is a subjective process whereby the tooth and the shade guide are observed simultaneously under the same lighting conditions. General variables such as external light conditions, experience, age, and fatigue of the human eye and physiological variables such as colour blindness may lead to inconsistencies and bias.[8,20] In addition, standardised verbal means for communication of visually assessed colour characteristics are limited.[36] Despite these limitations, the human eye is very efficient in detecting even small differences of colour between two objects.[37]

A number of methods for taking tooth shades visually have been described.[2,16] In general, the basic shade of a tooth is represented in only the middle third of the tooth[2] because the range of colour changes from the incisal to gingival areas, and the experienced observer must train himself to focus on this area.[38] The value should be selected first and rearrangement of the shade guide from the lightest to darkest is recommended.[16] The basic hue and chroma variations are then determined.

Although shade guides for prostheses commonly serve as the colour standard to which tooth colour is matched, several disadvantages have been described. For examples, the range of shades available is inadequate and does not cover the complete colour space of natural tooth colour;[39–44] the shades are not systematic in their colour space;[45,46] there is a lack of consistency among and within individual dentists in matching colours;[38,47,48] the results cannot be transformed into the CIE Lab colour scale;[49] and none of the commercially available shade guides are identical.[37,50,51]

Despite these limitations, the use of shade guides is a quick and cost-effective method for measuring tooth colour. They have been used successfully in a large number of tooth whitening studies where longitudinal changes in tooth colour have been measured.[13,52–57] The tooth colour discriminatory ability of individuals can be improved with training and experience.[8,58] Indeed, it is often reported that investigators undergo a number of colour calibration exercises and training with shade guides when conducting tooth whitening studies.[52-54,56,57]

A new shade guide has been described, which has been specifically designed for the selection of tooth rather than denture colour.[59] This system (3D-Master, Vident, Brea, CA) contains shade tabs that are uniformly arranged in the colour space of natural teeth. This shade guide has been shown to significantly improve repeatability of measuring tooth shade compared to a traditional shade guide for a group of general practitioners but not for a group of prosthodontists.[60]

Instruments such as spectrophotometers and colourimeters have been used in industrial and research settings for the measurement of colour of a wide range of materials and substrates.[61] Spectrophotometers measure one wavelength at a time from the reflectance or transmittance of an object and have been used to measure the visible spectra of extracted and vital teeth.[37,62-67] However, Tung et al.[68] have stated that the widespread use of spectrophotometers in dental research and clinical settings has been hindered by the fact that the equipment is complex and expensive and, more importantly, that it is difficult to measure the colour of teeth in vivo with these machines.

Colourimeters have colour filters that approximate the spectral function of the standard observer's eye and are generally designed to measure colour in *X*, *Y*, *Z* tristimulus terms or in CIE Lab values.[24,68] Much of the dental research on the natural colour of teeth in vitro and in vivo has been conducted with colourimeters.[10,36,38,40,41,49,68-74] Colourimeter measurements have been compared with spectrophotometer readings and deemed reliable and accurate for colour difference measurements.[24,69,70,75] In general, colourimeters have shown good repeatability of natural tooth colour measurements in vitro and in vivo.[68,71]

By using custom positioning jigs to ensure repeatable intra-oral positioning of the instrument's measuring aperture on the tooth surface, Douglas[71] has shown acceptable precision for the measurement of longitudinal changes in tooth colour in vivo. This approach has been used successfully in a number of clinical studies to evaluate tooth whitening from peroxide-containing products.[52,72,73,76-80] In addition, colourimeters have been used to measure colour changes of extracted teeth undergoing bleaching treatments.[74]

The results of investigations of the relationship between colour perceived by human observers and colour assessed by colourimeters have been inconclusive.[68] Some investigators[24,69] found a significant correlation between instrumental measurements and human observations, whilst others[38,70,75] reported no significant agreement.

The disadvantages of using colourimeters for measuring tooth colour include: the instruments are designed to measure flat surfaces, teeth are often not flat and can have surface anomalies, and small aperture colourimeters are prone to significant edge-loss effects so colour determinations will be subject to errors.[24,81] A further criticism of colourimeters is that systematic errors are difficult to manage and can be expected to adversely affect instrument accuracy regardless of degree of precision or control of environment.[71] In other words, inter-instrument agreement is relatively poor in comparison with intra-instrument reliability. Consequently, comparison of colourimetric data of teeth is discouraged and placing practical significance on independent measurements is unreliable.[71] The concept of measuring the colour of a tooth with a tristimulus colourimeter and using the data for verification of the shade match of a prosthesis would be affected by systematic inaccuracy. Douglas[71] concludes that the proper application of instrumental colourimetry involves exploiting its sensitivity in detecting and measuring small colour differences between samples of similar colour,[10] since differential measurement is highly reproducible between instruments and represents the most effective use of colourimetric evaluation.

Another approach for measuring tooth colour is via computer analysis of photographic images.[82-86] This approach has been successfully used to evaluate the bleaching effects of peroxide-containing products over time and expressing the colour changes in terms of CIE Lab values.[82,83] For example, after 14 days use of a 10% carbamide peroxide tray-based system, the mean change from baseline in L^* and b^* were 2.07 and -1.67, respectively.[85]

Tooth colour distribution

The range of colour and distribution of colour in different regions of the tooth have been described by a number of investigators. In general, the maxillary anterior teeth are slightly more yellow than mandibular anterior teeth,[40] and the maxillary central incisors are higher in value than the lateral incisors and canines.[40,64,67,87]

There are no significant differences in tooth colour between males and females according to a number of studies involving natural teeth.[23,67] In contrast, a recent study[7] has shown that compared to men, women had statistically lighter and less yellow teeth when tested at the population mean of a group of 180 people from the USA, with L^* approximately 3.7 units lower on average in males compared to females for maxillary central incisors. In this study, ethnicity was shown not to be a consistent predictor of tooth colour.

In general, natural tooth colour has a significant tendency to increase with the age of the subject, generally becoming darker and more yellow.[7,23,40,64,67,87-89] With advancing age, it has been reported that the colour can increase in redness at the incisal site because of the long term occlusal wear loss in the incisor region.[67] The impact of age on tooth colour is due to a number of factors. As the dental pulp ages it shrinks, leaving secondary dentine in its wake.[90] The surrounding dentine becomes harder and less permeable. At the same time, it has been hypothesised that pigments and ions of an amorphous organic and inorganic nature permeate through the enamel, depositing at the dentine-enamel junction and within the dentine structure.[90] The dentine chroma becomes more saturated and the overall value of the tooth becomes lower. Combined with an ever-decreasing enamel thickness as a result of normal wear, the dentine colour begins to dominate anterior tooth shade. Indeed, such thinning has been shown in vitro to contribute to increase in yellow when tooth colour is measured using a spectrophotometer.[9] The net result is a progressive darkening of the teeth associated with age. In the midst of a vast array of genetically determined tooth colours, all teeth darken over the course of time.[90] In addition, for a group of 180 USA adults and teenagers whose maxillary central incisors were measured with a spectrophotometer, it was shown that for each year of life, the average tooth colour shifted more into the yellow colour range by approximately $0.10b^*$ units, and the average lightness decreased by $0.22L^*$ units.[7] In the same study, it was shown that with increase in age, the mean level of b^* increased more rapidly in males compared to females. In addition, the consumption level of coffee or tea and level of dental care frequency significantly affected the magnitude of L^* and b^* when fitted to a regression model.[7] Individuals who consumed coffee or tea daily averaged a 1.2 unit increase in b^* and a 1.5 unit decrease in L^*.

The middle site of the tooth has been described as the site that best represents the colour of the tooth material.[40] This is because the incisal site is most often translucent and is affected by its background and because the cervical colour is modified by the scattered light from the gingiva.[22,91] To this end, Goodkind and Schwabacher[39,40] measured in vivo using a fibre-optic colourimeter calibrated with a spectrophotometer the colour co-ordinates of the middle facial surface of 2832 anterior teeth. The colour distributions were found to be hue 4.49 YR to 2.26 Y, value 5.66- 8.48 and chroma /1.09-4.96. The Munsell colour co-ordinates were highly correlated and closely confined to a planar region of the colour space.[91] Other studies which have quoted anterior tooth colour in either Munsell, chromaticity or tristimulus co-ordinates have been summarised by Miller[50] and O'Brien et al.[22] Studies that have measured the colour of the maxillary central incisor in vivo and reported in CIE Lab colour space are summarised in Table 1. These studies indicate a range of natural tooth colours.

Hasegawa et al.[67,87] measured the colour in five different locations along the tooth axis of the labial surface of the central incisors using spectrophotometry and found significant variations in $L^*a^*b^*$ values along this axis. For L^*, the lightest portion of the tooth was in the centre (ca. 73). The magnitude of L^* was lower towards the cervical area (ca. 69) and significantly lower towards the incisal edge (ca. 64). For a^*, the highest values were found in the cervical area (ca. 8.5) and was gradually and significantly lower towards the incisal edge (ca. 2.0). For b^*, again the cervical region was the highest (ca. 20) with gradual and significant reduction in b^*

Table 1 Reported $L^*a^*b^*$ values for central maxillary incisors measured in vivo.

Reference	Method	Subject demographics			Colour co-ordinates		
		Country	Number	Age (years)	L^*	a^*	b^*
Gegauff et al.[78]	Colourimeter	USA	20	20-27	51.1	−0.1	−0.2
Rubino et al.[41]	Colourimeter	Spain	600	15-50	67.6 ± 7.0	4.3 ± 2.1	12.1 ± 3.3
Zhao and Zhu[64]	Spectrophotometer	China	70	18-70	51.48 ± 8.02	0.62 ± 0.14	0.15 ± 0.02
Odioso et al.[7]	Spectrophotometer	USA	180	13-64	69.3 ± 5.92	5.4 ± 1.33	18.7 ± 3.37
Russell et al.[65]	Spectrophotometer	Ireland	7	Dental students	48.31	1.35	2.73
Russell et al.[65]	Spectrophotometer	Ireland	7	Dental students	41.31	−0.91	4.91
Hasegawa et al.[67]	Spectrophotometer	Japan	87	13-84	73.0 ± 5.0	3.5 ± 1.5	16.5 ± 5.0

towards the incisal region (ca. 13). The translucency of natural teeth was also shown to decrease from the incisal site towards the central site.[87]

O'Brien et al.[22] found similar results when measuring the colour of 95 extracted anterior teeth from 35 patients using a spectrophotometer in vitro. The mean L^*, a^* and b^* values, respectively, were 72.6, 1.5 and 18.4 for gingival, 72.4, 1.2 and 16.2 for middle, and 71.4, 0.9 and 12.8 for incisal regions. The differences between these regions are statistically and clinically significant. Thus, there is an overall gradation in colour from the cervical region, which is the most saturated, to the incisal region.

Allowing teeth to dry out has been shown to make the teeth appear whiter.[2,65] For example, Russell et al.[65] applied a rubber dam to the anterior teeth of seven subjects and allowed the teeth to dry out for 15 min. The colour of the teeth were measured before and after with a spectrophotometer and it was shown that L^* significantly increased, a^* significantly increased towards zero whilst b^* showed no significant change. Thus, the colour of the teeth had become lighter and less saturated. The colour of the teeth returned to their baseline values after 20 min from the removal of the rubber dam. In addition, polyvinylsiloxane impressions had a similar effect on tooth colour, but required at least 30 min in order for them to regain their original baseline colour.

Tooth colour perception and appearance

In contemporary dentistry, the needs of patients are considered in terms of function and dental appearance. The appearance of the teeth is related to both cultural factors and individual preferences, i.e. the viewer's perception of a visual experience can be pleasant or unpleasant, and what is considered 'beautiful' in one culture may be 'ugly' in another.[3] The most common associations with facial attraction are the eyes and mouth.[92] The oral region plays an important role when an individual speaks or approaches another person and, for example, poor oral hygiene and ugly teeth are noticed by others.[3] In addition, the subjects' perception of tooth whiteness, health and attractiveness is greatly influenced by the colour of the adjacent lips and gums.[93]

In a dental aesthetics attitudes survey[3] of 254 subjects, it was found that the appearance of the teeth was found to be more important to women than men and significantly more important to younger people than older. In addition, the perception that very white teeth are beautiful significantly decreased with increasing age of the subject, and younger subjects expressed a greater preference for white teeth than older subjects. This was in agreement with a study where photographs of four maxillary dentures, identical except for shade, were rank ordered for preference by 150 subjects, where it was found that older subjects preferred darker colours than younger subjects.[94]

Grosofsky et al.[95] manipulated the colour of the teeth in head-and-shoulder photographs and subjects were asked to rate attractiveness. Subjects' ratings of attractiveness were not influenced by tooth colour. This suggests that manipulating tooth colour to make teeth whiter does not make an individual more attractive or younger appearing. It was speculated that one possible reason for tooth whitening may be the association with increased self-esteem. Indeed, Ashworth et al.[96] found that cosmetic dental changes, such as a porcelain veneer attached to the anterior teeth of participants with dental abnormalities, are related to enhancements in perception of self.

The satisfaction of personal tooth colour was investigated in a study[7] with 180 adults aged between 13 and 64 years. Despite the 55–64 years group having significantly darker and more yellow teeth than the 13–17 years group, both groups expressed similar levels of satisfaction with their personal tooth colour, 30 and 27%, respectively. It was speculated that differential expectations exist among the age groups that may affect tooth colour satisfaction, and so individuals may seek to have whiter teeth within their peer group rather than the whitest teeth possible. In the same study, it was found that individuals who had fewer than two dental visits per year were less satisfied with their current tooth colour than those who had two or more.

The subjective first-person response for having teeth bleached was investigated in a study involving 50 adults and the use of two self-directed hydrogen peroxide-containing products over two weeks.[82] The tooth colour was objectively measured before and after treatment and a subject questionnaire was completed after treatment. It was found that the subjective responses to whiteness improvement and satisfaction were significantly correlated with changes in b^* and not L^* or a^*. Thus, the yellow–blue shift is of primary perceptual importance to the user of vital tooth bleaching products.[83]

In addition to value, hue and chroma, other more subtle secondary optical properties of the tooth exist and which can affect the overall appearance of the tooth. These have been reported to include translucency, opacity, iridescence, surface gloss and fluorescence.[5] Translucency and opacity have been viewed as the most important of these secondary properties, since they are an indication of the quality and quantity of light reflection.[97] The cervical regions have been shown to have the lowest translucency.[87] Iridescence produces a rainbow effect within the object being viewed. Varying degrees of iridescence can be observed depending on the direction, location and illumination of an object, and is dependent on the wavelengths of dispersion, diffraction and interference of light.[5] Surface gloss affects the appearance and vitality of teeth.[5] On the labial surface of anterior teeth, light reflected from tertiary anatomy adds to vitality, whereas less vitality is evident when this anatomy is worn with age. The tooth surface morphology affects the amount and type of reflection—a rough or coarse surface allows more diffuse reflection whilst a flat smooth surface allows more specular reflection. For example, the amount of light reflection at tooth enamel surfaces in vivo following toothbrushing have been shown to significantly increase.[66]

It has been suggested that perceived appearance within the dental environment is too complex to be completely defined by three colour parameters.[69] Since the perception of appearance of teeth includes many factors including the concepts of colour, translucency, gloss, etc. the simple specification of three colour parameters derived from an instrument for a given illumination and observation geometry would be incomplete in solely determining the appearance of a translucent material.[69] Thus, the usefulness of instrumental measurement techniques as a clinical tool has been questioned,[38] although developments are always ongoing in order to improve tooth colour measurement methods and techniques. However, in the final synopsis, regardless of the instrumental technique used in the evaluation of tooth colour, the ultimate assessments are visual ones.[72]

Conclusions

The colour and appearance of teeth is a complex phenomena, with many factors such as lighting conditions, translucency, opacity, light scattering, gloss and the human eye and brain influencing the overall perception of tooth colour. The measurement of tooth colour is possible via a number of methods including visual assessment with shade guides, spectrophotometry, colourimetry and computer analysis of digital images. Each method has its own limitations and set of advantages and disadvantages. Nevertheless, these methods have successfully been used to measure longitudinal tooth colour changes when the dentition has undergone tooth whitening procedures. With the continued interest in tooth whitening by patients and consumers, methods and techniques for determining and improving tooth colour will continue to evolve with time and the likely spin-offs will no doubt be of great benefit to the field of aesthetic dentistry.

Acknowledgements

The author would like to thank Mike McGrady of 4-Front Research, Capenhurst for his help in the preparation of the manuscript.

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