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A novel method for testing the veridicality of dental colour assessments

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SUMMARY The Commission Internationale de l'Eclairage (CIE) L*a*b* three-dimensional coordinates suggest strong correlations between the data of a* (red–green axis) and b* (blue–yellow axis), as both are located on the same plane in the model and should therefore show a strong dependency. In order to assess the veridicality of colour determinations, the null hypothesis of no significant changes in CIE-a*/b* coherences of dental colours following a colour or lightness change induced by external dental bleaching was tested.

Values from 231 extracted anterior teeth were assessed using the digital photographic CIELAB recalculation method. Teeth were then assigned to three groups (n = 77) with contrasting baseline CIE-L* values. Group A served as the control with no alteration in dental colour. The specimens in the two other groups were altered in colour or lightness employing treatment with either 15 per cent carbamide peroxide (group B) or 38 per cent hydrogen peroxide (group C). Pearson's pairwise correlation coefficient of CIE-L*; a*, CIE-L*; b*, and CIE-a*; b* were calculated for assessments at baseline (T0) and after 2 (T1), 4 (T2), 12 (T3), and 24 (T4) weeks.

The correlations of a* and b* from T0 to T4, in relation to group A, were stable, with coefficients of 0.78→0.65→0.65→0.69→0.67. Bleaching-induced colour and lightness changes did not have a significant influence on the a*/b* coherences assessed. A distinctly weaker and inverse relationship was observed between L* and a* values and between L* and b* values in the groups, with correlation coefficients ranging from −0.54 to −0.12. Colour coherences detected at specific points in time were in agreement with theoretical CIE colour coherences. In order to compare the methodology of different colour analyses, the analysis of correlations between CIE-a* and -b* values is advocated as an additional routine test in future CIELAB studies.

Introduction

Colour assessments are an integral part of everyday dental practice (Fani *et al.*, 2007; Joiner *et al.*, 2008) and are also gaining importance within the field of orthodontic research, with an increasing number of trials on intra-oral ageing-related colour alterations of plastic or ceramic brackets, elastics, power chains, and adhesives (Eliades *et al.*, 2004; Kim and Lee, 2009). Moreover, with increasing awareness of multibracket-induced white spot lesions, their treatment and subsequent screening, a new field are emerging within the orthodontic profession (Knösel *et al.*, 2007). The results of studies concerning the colour properties of dental materials or the efficacy of dental bleaching and the staining potential of different foods or agents are meaningless unless they are based on reliable methods of colour assessment. In contrast to more or less subjective shade tab assessments (Leonard *et al.*, 2001; Hammad, 2003), the Commission Internationale de l'Eclairage, L*, a*, and b* system (CIELAB) has been established as a more objective method, and one that is more appropriate for scientific purposes, as it provides the possibility of setting parameters, which can be compared using statistical tests (CIE-Colorimetry, 1978; Johnston and Kao, 1989; Bengel, 2003; Karamouzos *et al.*, 2007; Ziebolz *et al.*, 2007; Joiner *et al.*, 2008). Nevertheless, the methods currently used for obtaining CIELAB values show variation in accuracy and, in addition to shortcomings in the methods of assessment themselves, the influence of experimental and ambient conditions has also raised concerns (Knösel *et al.*, 2009). These include ambient light, the experimental set-up (which can be *in vivo* or *in vitro*), the shape of the assessment field, and the diligence of the assessor. These factors play an increasingly important role the longer the assessment requires to be carried out and the greater the detail there is in relation to the results.

In order to determine method error and to obtain reliability assessments, it is common practice in CIELAB dental research to determine the accuracy of the method employed by using repeated measures analyses. For this purpose, colour and lightness values are either judged independently or are summarized as ΔE-values, which are defined as the Euclidean distance in three-dimensional (L*, a*, and b*) space for two different levels of a parameter (par 1 and par 2, which can be either time points or groups):

$$\Delta E_{(\text{par1-par2})} = [(L_{\text{par1}} - L_{\text{par2}})^2 + (a_{\text{par1}} - a_{\text{par2}})^2 + (b_{\text{par1}} - b_{\text{par2}})^2]^{1/2}.$$

Whereas these analyses are able to depict variations in the reproducibility of measurements, they do not, however, allow conclusions to be drawn about the veridicality or validity of the colour variables being assessed. However, in order to obtain an objective dental colour assessment unaffected by method errors, it is favourable to obtain CIELAB parameters that depict, as far as possible, the actual colour appearance, with method-dependent errors remaining as small as possible.

In order to establish the ability of a colour method to provide CIELAB parameters that are likely to depict actual colour appearance, a comparison of theoretical coherences given by the structure of the CIELAB colour system can be used. This approach is based on the assumption of a consistency in chromaticity correlations independent of colour and lightness changes: the CIE-parameter L* corresponds to the degree of lightness, while a* and b* values give the position on the red or green (+a* = red and −a* = green) and yellow or blue (+b* = yellow and −b* = blue) axes (Figure 1). In the model, the chromaticity parameter is judged separately from the lightness parameter, the latter being represented by an additional axis (CIE-Colorimetry, 1978). This means that the uniform CIELAB colour system implies strong coherences between the chromaticity data in terms of the values a* (red–green axis) and b* (blue–yellow axis) as both are located on the same plane in the model and should therefore display a strong dependency. However, their interaction can also be assumed to be independent of the lightness parameter L* changes. So, baseline CIE-a*/b* colour coherences are supposed to be stable in the presence of changes in colour or lightness, both of which are typical for experimental observations made in CIELAB clinical trials, and the stability in recording chromaticity coherences may represent a measure of the reliability and validity of the CIELAB measurements.

The aim of the present study was therefore to exemplarily test one CIELAB analysis in terms of its veridicality and consistency in assessing colour coherences, by comparing assessed chromaticity and lightness correlations with reference to CIE-L*, a*, and b* values compared with theoretical correlations of the colour system, before, during, and after a change in colour and lightness induced by two different, external, and dental bleaching regimen.

The null hypothesis tested was that correlations of colour parameters a* (red–green axis) and b* (blue–yellow axis) assessed with CIE colour calculations based on digital dental photography (Bengel, 2003; Elter *et al.*, 2005; Jarad *et al.*, 2005; Wee *et al.*, 2006; Ziebolz *et al.*, 2007; Knösel *et al.*, 2009) change significantly after lightness and colour changes induced by external bleaching, i.e before (T0), 2 (T1), 4 (T2), 12 (T3), and 24 (T4) weeks after whitening with two different bleaching regimens compared with a non-bleached control group.

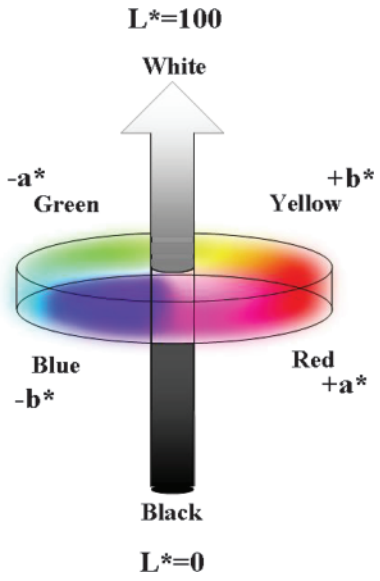

Figure 1 The Commision Internationale de l'Eclairage-L*a*b* colour system.

Materials and methods

Two hundred and thirty-one human permanent anterior teeth extracted because of periodontal decay were selected, with exclusion criteria of decay, fillings, and restorations. The teeth were stored in isotonic sodium chloride solution (Braun, Melsungen, Germany) under dark ambient conditions at 20°C. Prior to commencing the bleaching trial, the teeth underwent a stratified randomization process and were assigned blindly with reference to L*-values to the three trial groups with nearly identical mean baseline L*-values: control group A ($n = 77$; L* 68.16 ± 3.84), group B 15 per cent carbamide peroxide ($n = 77$; L* 68.23 ± 3.79), and group C 38 per cent hydrogen peroxide ($n = 77$; L* 68.32 ± 3.7). Overall mean L* value was 68.24 ± 0.8.

Prior to dental colour assessments, the teeth were slightly dried of the artificial saliva solution in which they had been stored between colour assessments (Attin *et al.*, 2000), in order to minimize light reflections during colour assessments and to prevent enamel colour alterations caused by drying (Russell *et al.*, 2000). Prior to colour assessments, the teeth were professionally cleaned using a non-fluoride polishing paste (Clean Polish, Kerr Hawe, Bioggio, Switzerland).

Standardized CIE (L*a*b*) colour assessments were performed by processing digital images for colour calculation using AdobePhotoshop™ software (Adobe Systems Inc., San Jose, California, USA); the method has been tested previously with a good level of reproducibility (Ziebolz *et al.*, 2007; Wiegand *et al.*, 2008; Knösel *et al.*, 2009). To achieve true dental colours for the teeth to be measured, the colour and brightness of the digital images were backward processed to the original tone of a reference patch with known grey scales and a reflectance value of 18 per cent (QP Card 101; QPcard AB, Göteborg, Sweden),

which was placed as a neutral colour reference on the tooth. Details of the colour recalculation procedure have been published (Bengel, 2003; Knösel *et al.*, 2009).

A custom-made fixture was used in order to standardize the distance between the tooth measured and the camera lens (15 cm), as well as camera angle (0 degrees). Exposure time (1/60 second) and aperture (32) were identical for all image recordings. Digital images were obtained using a Canon EOS 350D with a macro lens (EF 100 mm 1:2.8 USM; Canon Inc., Tokyo, Japan) and a macro ring flash (Canon MR 14 EX). Illumination during all sessions was achieved using identical ambient illumination with the exclusion of daylight.

CIE (L*a*b*) data were collected after 2 (T1), 4 (T2), 12 (T3), and 24 (T4) weeks to baseline (T0) data. All colour assessments as well as CIELAB colour calculations were performed by one operator (MR). The set-up for the study is illustrated in Figure 2.

Assessment of repeated measurement accuracy

At T0, CIE (L*, a*, and b*), the data for every tooth were analysed three times to assess the accuracy of repeated measurements. The total of 231 × 3 pre-trial colour assessments yielded a variance of 7 per cent for the parameter lightness (median range of ΔE 1.9), 4 per cent for the parameter a* (ΔE 0.1), and 2 per cent for the parameter b* (ΔE 0.3). The total number of colour assessments (repeated baseline assessments and trial assessments) was 1617.

Dental colour and lightness alteration

A change in colour and lightness was induced by external bleaching. Accordingly, group B was treated with 15 per cent carbamide peroxide solution (Opalescence PF; Ultradent, South Jordan, Utah, USA) on five consecutive days for 8 hours each. Frasaco strip crowns (Frasaco, Tettnang, Germany) served as standardized single trays for bleaching gel application on the single teeth during storage of the incisors in artificial saliva. Enamel colour alteration in group C was performed three times on three consecutive days using a 38 per cent hydrogen peroxide solution (Opalescence XtraBoost, Ultradent).

Statistical analysis

Repeated measurement analysis of variance (ANOVA) models were used to test for changes over time and group differences for each CIE coordinate independently. This also included a test of homogeneity between groups at T0. *P*-values for multigroup comparison within the ANOVA models were adjusted for multiple testing by the method of Tukey.

Linear correlations of CIE-L*, a*, and b* values were calculated in a trial-group-specific manner and partialized for the three trial groups. Homogeneity of the group-specific correlations was tested by application of a fixed effect meta-analysis model on Fisher's *Z*-transformed correlation coefficients. In order to assess any change in the correlation of a*/b* by brightness variation, CIE-L* values were first classified by lightness into four quartiles. Then, the correlation of a*/b* within every group, time point and L*-quartile was estimated. ANOVA models were used to test the influence of CIE-L* changes on *Z*-transformed correlation coefficients, weighted by the inverse of the variance which is known to be $\mathrm{var}(z) = 1/(n-3)$. Models were fitted to the partial and to the group-specific correlation estimates, adjusted for group or time point, if adequate.

The significance level was set to $\alpha = 5$ per cent. Statistical analysis was carried out using SAS 9.1 (SAS Institute, Cary, North Carolina, USA).

Results

Bleaching procedure effects

Groups A, B, and C showed no significantly different colour and lightness properties in relation to parameters L*, a*, or b*. Repeated measurements ANOVA revealed a significantly different development in colour and lightness following bleaching compared with group A [L*, a*, and b* (all $P < 0.001$)]. Direct comparison of both bleaching groups B and C also revealed group differences for L* (all $P < 0.001$).

Lightness and chromaticity correlation

No significant heterogeneity between the correlation patterns of CIE of the trial groups was found [P (L*−a*) = 0.39, P (L*−b*) = 0.1, and P (a*−b*) = 0.8]. Figure 3 shows the positive correlation of CIE-a* and -b*, which was strongest at T0: 0.77 (group A), 0.79 (B), and 0.77 (C). During the follow-up assessments, this correlation decreased slightly to the level of ~0.65 (T1–T4: 0.65→0.65→0.69→0.67), consistently for all trial groups. The partial correlations of L* to a* and to b* were, in general, significantly negative at a moderate level between −0.26 and −0.54 (all $P < 0.001$), except for T1 assessments, where non-significant low negative correlations were found (both −0.12, $P > 0.05$). Thus, differences in the correlation pattern between trial groups were observed. No significant correlation between L* and a* or L* and b* values was observed at T0 for group A [P (L*−a*) = 0.13 and P (L*−b*) = 0.42] and at T1 for the groups B and C (all $P > 0.5$; Tables 1 and 2).

Figure 2 Design of the study. The Commision Internationale de l'Eclairage (L*a*b*) assessments were conducted at T0 (baseline), and after 2 (T1), 4 (T2), 12 (T3), and 24 weeks (T4).

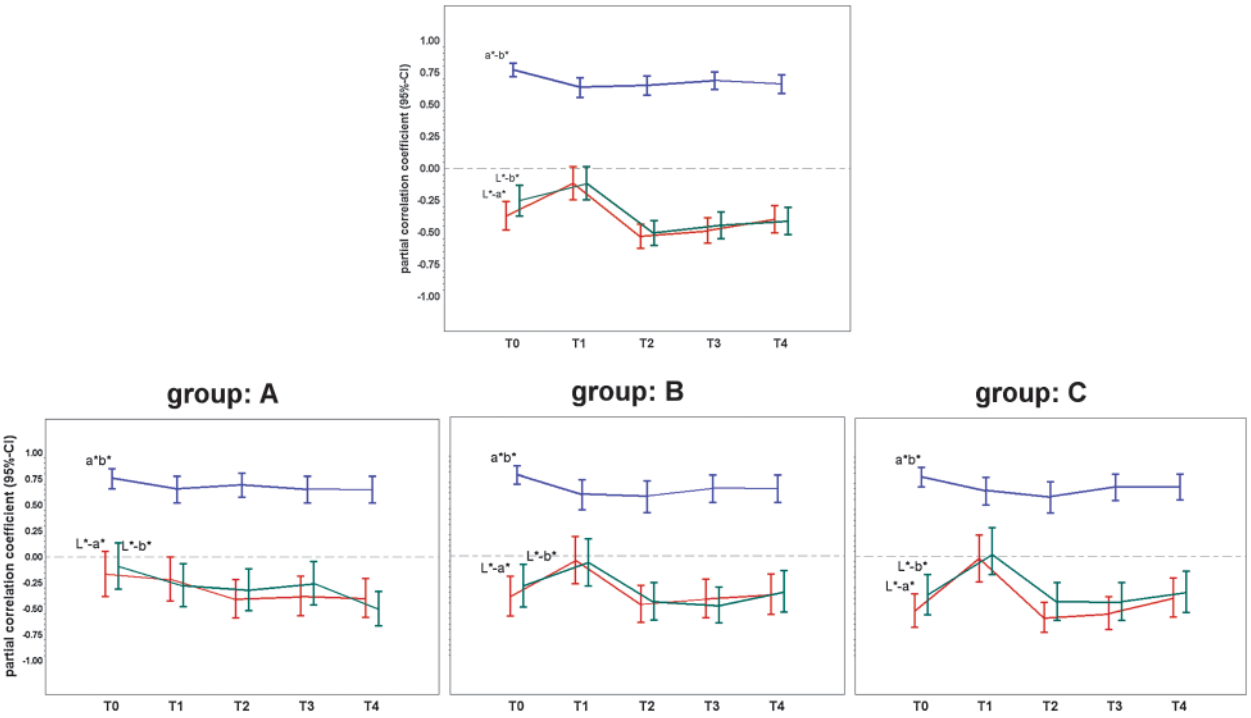

Figure 3 Correlations and coherences of colour and lightness values from baseline (T0) to 24 weeks (T4).

In order to assess the impact of lightness changes (CIE-L*) on the correlation of a*/b*, several ANOVA models were used. No significant influence of value L* was observed, either regarding partial correlations ($P = 0.9$) or group-specific correlation ($P = 0.84$ for estimating one effect for all trial groups and $P = 0.82$ for estimating different effects for the trial groups; Table 3).

Hence, no significant modification of the correlation structure between CIE-colour dimensions was caused by external bleaching. The null hypothesis of significant changes in chromaticity and lightness correlations following changes in lightness and colour as a result of external bleaching was rejected.

Discussion

The quality of dental CIELAB recordings can be judged in relation to the two aspects of repeatability of the assessed results, on the one hand, and the veridicality and reliability of the assessed values, on the other. For example, when CIELAB results derived by different methods are compared, it is often the case that they are reproducible with one method but that metric colour values often do not match those derived using another, but over- or underscore values, especially chroma values (Joiner *et al.*, 2008). Unfortunately, there is no gold standard against which assessed colours can be evaluated, which is especially problematical, as the quality of CIELAB assessments is often influenced by inconsistencies in ambient conditions. Bearing in mind the lack of a gold standard and the fact that chromaticity correlations can be theoretically expected to be independent of changes in colour and lightness in this study, a decision was made to carry out colour assessments before and after dental bleaching and to assess the influence on chromaticity and colour/lightness coherences.

Deviations from theoretical chromaticity and lightness coherences

In answering the question posed by this study, to clarify whether the CIELAB calculation method used here (Knösel *et al.*, 2009) for dental colour analysis distorts or falsifies the chromaticity coherences on which the CIELAB colour system is based, the assumed large chromaticity coherences of the significant CIE-a*/b* correlation coefficients obtained throughout the trial were confirmed. There was a constancy in assessing chromaticity coherences reflected in the highly significant correlation coefficients found throughout the complete trial, for all groups, regardless of whether there was a colour or lightness change produced by external bleaching treatment or not, with no significant differences between the 15 per cent carbamide peroxide group and the group subjected to the more efficient 38 per cent hydrogen peroxide bleaching.

However, CIE-values a* and b* did not show a pure linear coherence throughout the test series. Moreover, despite there being no significant correlations between lightness and chromaticity values at T0 in group A and at T1 after bleaching, in contrast to the hypothesis, some significant coherences between those values were found later (Table 1). Although confidence intervals obtained when assessing summarized CIELAB correlations (groups A–C) were larger for lightness/

Table 1 Pearson's product-moment correlation coefficients of the Commission Internationale de l'Eclairage (CIE) system chromaticity and lightness values, displayed separately for the three trial groups, at baseline (T0), and after 2 (T1), 4 (T2), 12 (T3), and 24 (T4) weeks.

		Pearson's correlation coefficient *r* (95% confidence interval)		
		CIE-L* versus CIE-a*	CIE-L* versus CIE-b*	CIE-a* versus CIE-b*
Control group A	T0	−0.17 (−0.38 to 0.05)	−0.09 (−0.31 to 0.13)	0.77*** (0.66 to 0.85)
	T1	−0.22* (−0.43 to 0.00)	−0.29* (−0.48 to −0.07)	0.67*** (0.52 to 0.78)
	T2	−0.42*** (−0.59 to −0.22)	−0.33** (−0.52 to −0.12)	0.71*** (0.57 to 0.80)
	T3	−0.39*** (−0.57 to −0.18)	−0.26* (−0.46 to −0.04)	0.67*** (0.52 to 0.78)
	T4	−0.41*** (−0.58 to −0.21)	−0.52*** (−0.66 to −0.33)	0.67*** (0.52 to 0.77)
Group B (carbamide peroxide bleaching)	T0	−0.40*** (−0.57 to −0.19)	−0.30** (−0.49 to −0.08)	0.79*** (0.68 to 0.86)
	T1	−0.04 (−0.27 to 0.18)	−0.07 (−0.29 to 0.16)	0.60*** (0.44 to 0.73)
	T2	−0.48*** (−0.63 to −0.28)	−0.45*** (−0.62 to −0.26)	0.59*** (0.42 to 0.72)
	T3	−0.42*** (−0.59 to −0.22)	−0.49*** (−0.64 to −0.30)	0.66*** (0.51 to 0.77)
	T4	−0.38*** (−0.56 to −0.18)	−0.36** (−0.54 to −0.14)	0.66*** (0.51 to 0.77)
Group C (hydrogen peroxide bleaching)	T0	−0.54*** (−0.68 to −0.36)	−0.38*** (−0.56 to −0.17)	0.78*** (0.67 to 0.85)
	T1	−0.02 (−0.25 to 0.20)	0.05 (−0.17 to 0.28)	0.65*** (0.49 to 0.76)
	T2	−0.61*** (−0.73 to −0.44)	−0.45*** (−0.61 to −0.25)	0.59*** (0.42 to 0.72)
	T3	−0.56*** (−0.70 to −0.39)	−0.45*** (−0.61 to −0.25)	0.68*** (0.54 to 0.79)
	T4	−0.41** (−0.58 to −0.21)	−0.36** (−0.54 to −0.14)	0.68*** (0.54 to 0.79)

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Table 2 Correlation of the Commission Internationale de l'Eclairage (CIE) colour dimensions, summarized for all groups.

	Pearson's correlation coefficient *r* (95% confidence interval)		
	L*–a*	L*–b*	a*–b*
T0 (baseline)	−0.38*** (−0.48 to −0.26)	−0.26*** (−0.37 to −0.13)	0.78*** (0.72 to 0.82)
T1 (2 weeks)	−0.12 (−0.24 to 0.01)	−0.12 (−0.24 to 0.01)	0.64*** (0.56 to 0.71)
T2 (4 weeks)	−0.54*** (−0.62 to −0.44)	−0.51*** (−0.60 to −0.41)	0.65*** (0.57 to 0.72)
T3 (12 weeks)	−0.49*** (−0.58 to −0.39)	−0.45*** (−0.55 to −0.34)	0.69*** (0.62 to 0.75)
T4 (24 weeks)	−0.40*** (−0.51 to −0.29)	−0.42*** (−0.52 to −0.30)	0.67*** (0.59 to 0.73)

Pearson's product–moment correlation, calculated partially for trial groups.
* *P*-value <0.05; ** *P*-value <0.01; *** *P*-value <0.001.

chroma than for chromaticity correlations, these deviations from assumed theoretical coherences may be viewed as an indicator of inaccuracies of a method which may have an impact on the validity of the recordings. Underneath those lightness/chromaticity correlations which may be due to colour and lightness changes brought about by bleaching, similar correlation changes in the group A were also found, although at a lower level of significance. If the assumption of a dependency between chromaticity recordings at the same time as an independence of chromaticity recordings from lightness and colour changes is valid, then the correlation changes in the group A are likely to be attributable to a measurement error, due to a failure to record true chromaticity values.

For a*/b* colour coherences, only positive correlations were found, whereas for all L*/a* and L*/b* correlations, there were only negative correlations and only some of these were significant. Negative correlations between L* and a* or between L* and b* indicate that the higher the degree of lightness (+L*), the more bluish (−b*) and greenish (−a*) the colour appearance. Values a* and b* showed a stronger correlation than those between colour and lightness values. This strong correlation was not influenced by a change in the lightness of the teeth.

To date, as no data have been available for this type of chromaticity and lightness correlation test in the field of dental research, it is difficult to compare the method used against other CIELAB methods or to make an estimation of the impact of chromaticity and lightness correlation distortions recorded on measurement accuracy or the validity of assessed colours. Other research work groups can apply this additional test to the CIE-L*a*b* recording methods they are already using, such as spectrophotometry or colorimetry, in order to obtain a database for comparison of the ability of those methods in relation to the validity of colour assessments and in order to depict the accuracy of various CIELAB methods in greater detail (Joiner *et al.*, 2008). These additional chromaticity and lightness correlation tests may be of value, especially during long-term *in vivo* trials, where there may be inconsistencies in clinical settings, in terms of slight variations in ambient conditions.

Table 3 Significance of correlation of Commission Internationale de l'Eclairage (CIE) –a*–b; in dependence from CIE-L (double asterisks indicate test for one unified effect across trial groups).

Correlation a*–b*		*P*-value for trend over L*	
		Partial to trial group	Per trial group
T0 (baseline)	Overall	0.45	0.40**
	A		0.58
	B		0.80
	C		0.58
T1 (2 weeks)	Overall	0.57	0.93**
	A		0.36
	B		0.51
	C		0.75
T2(4 weeks)	Overall	0.15	0.55**
	A		0.65
	B		0.83
	C		0.78
T3(12 weeks)	Overall	0.62	0.38**
	A		0.52
	B		0.64
	C		0.11
T4 (24 weeks)	Overall	0.48	0.86**
	A		0.92
	B		0.27
	C		0.51

Study limitations and clinical implications

A limitation of the study may be the way that the new approach to testing the veridicality and reliability of assessed colour and lightness values (by comparing theoretically predicted and recorded chromaticity correlations) was first applied to just one CIELAB method. But, it was a preliminary project requiring the subsequent application of this type of test to other methods, such as colorimeters (Knösel *et al.*, 2007) or spectrophotometers (Karamouzos *et al.*, 2007; Browning *et al.*, 2009), in order to establish more precisely the accuracy of different approaches to describing dental colours. It is considered that the proposed colour coherence stability test is an additional easy to use and promising tool for a more specific characterization of the quality of dental CIELAB assessments.

Conclusions

Based on the findings of this study, the following conclusions can be drawn:

1. Colour and lightness changes induced by dental bleaching did not significantly distort baseline chromaticity coherences assessed by a digital photographic CIE-L*a*b* calculation, so that its application yields valid results.
2. Testing of CIE-a*/b* correlations at all points in time in future studies may be considered to be an indicator for the veridicality and reliability of the respective CIE-L*a*b* method employed and may be viewed as an additional routine test when reporting on dental chromaticity and lightness changes in clinical trials.

Conflict of interest

The authors declare that they have no conflict of interest.

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