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SCIENTIFIC SECTION

Colour changes of orthodontic elastomeric module materials exposed to *in vitro* dietary media

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Objective: To evaluate the colour stability of orthodontic elastomeric module material exposed to dietary media.

Design: An *in vitro* laboratory study

Materials and methods: Coloured and clear orthodontic elastomeric modules from four companies were exposed to coffee, cola, tea and spices for 72 h. The difference in colour components was measured with a Minolta chromameter before and after exposure.

Results: Significant changes in colour, including grey level and chromaticity, both as a function of colour and company of elastomeric ligature module were found following exposure to beverages and spices. Colour change was most affected by Δb^* (yellowness) and most significant in clear modules. Modules made using injection mouldings were more resistant to colour change than those by extrusion. Spice mix had the most effect and cola beverage the least. Clinically, these changes compromised both colour stability and esthetics of the elastomeric module.

Conclusions: Clinicians should make patients aware of the effect of consuming beverages and spices on the colour stability of their selected ligature modules. Clinicians should favour modules made with injection moulding. Darker colour modules may be preferred to clear modules to avoid excessive colour degradation through dietary media such as beverages and food spices. Patients consuming large amounts of spices or coffee should avoid clear modules made by extrusion processing because of their tendency to discolour.

Key words: Colour, orthodontic materials, staining, elastomers, aesthetics

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Introduction

Elastomeric modules have been a common part of orthodontic practice since their introduction more than 30 years ago.[1] These chains and single ligatures are manufactured by many companies and available in a variety of different colours to meet the growing global demand for aesthetic orthodontic appliances. Orthodontists and patients alike have developed a more discerning eye and preference for colour selection and more aesthetic braces. The clinician and patient may chose an aesthetically pleasing colour for the ligatures at the time of placement, but beyond this initial colour choice, the susceptibility for colour degradation of the modules over time is of critical concern. Orthodontic elastomeric modules are made from polyurethane using a die-stamping or injection-moulding process.[2–4] The die stamping process consists of two steps: the first step uses an extrusion process to produce bulk sheets of the polyurethane. In the second step the die stamp cuts the sheet into the final shape and size.

Concerns have been raised regarding the quality of the products and whether one company is superior to another in efficacy or cost-effectiveness. Many studies have been carried out comparing product performance such as force decay, friction and dimensional changes of these elastomeric modules.[5–9] For example, the question as to whether force delivery is affected by pigmenting of the elastomer has been studied elsewhere.[6,9] Structural conformation and degradation have also been examined.[11–15] Although the modules have been reported to be susceptible to staining in the oral environment, to the best of our knowledge, no systematic studies on colour stability of these modules have been reported previously.[16] The ability to prevent intrinsic and extrinsic stains of the polyurethanes modules has become an important challenge, as the oral environment is exposed to a variety of media on a daily basis, many of which

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may stain or alter the surface of modules causing aesthetic degradation. It is therefore important to know, not only whether long-term exposure to daily beverages and spices changes the colour of the module, but also whether it is a change that is perceivable by the human eye.

Colour plays an important role in many aspects of dentistry, particularly shade matching of restorations and tooth whitening products.[17] Several studies have been carried out on the staining effects of beverages namely, coffee, tea and wine, which are normally associated with adult tooth stain on composite restorations and tooth bleaching.[18–22]

Extended exposure to cola is known to cause colour changes of restorative composites.[21,22] and may also cause discolouration of orthodontic elastomeric ligature modules. Spices and seasoning are also known to cause extrinsic staining of teeth. They are essential in processed foods (prepared foods, snacks, sauces, condiments, salad dressings) and ethnic foods, especially Mexican, Italian, and Asian.

The objective of this study was to evaluate the role of spices and beverages namely, coffee, tea and cola in the discolouration of popular clear and coloured elastomeric modules used in orthodontics. The study examined whether colour changes of elastomeric modules due to dietary media exposure varied by:

- colour of module;
- manufacturer;
- type of dietary media.

Materials and methods

Elastomeric modules available in different colours from four companies were studied: American Orthodontics (Sheboygan, WI, USA), Ormco/Sybron (Orange, CA, USA), TP Orthodontics (La Porte, IN, USA) and 3M/Unitek (Monrovia, CA, USA). The modules were produced by either injection moulding or extrusion/die stamp. The colours studied included clear, white, grey, green, blue, charcoal and red. Not all colours were available from all companies. The initial shades of the module were matched visually as best as possible; however there were some differences in the shade of the same colour among companies. The soaking dietary media used was coffee (Ellis 100% Colombian, PA, USA), tea (Lipton Orange Pekoe and Pekoe cut black tea, Unilever USA, NJ, USA) brewed per the manufacturer's instructions, cola (Coke Classic), and two teaspoons of spice mix (McCormick's Indian Curry Powder Mild, McCormick & Co., Inc., MD, USA) in 250 ml water.

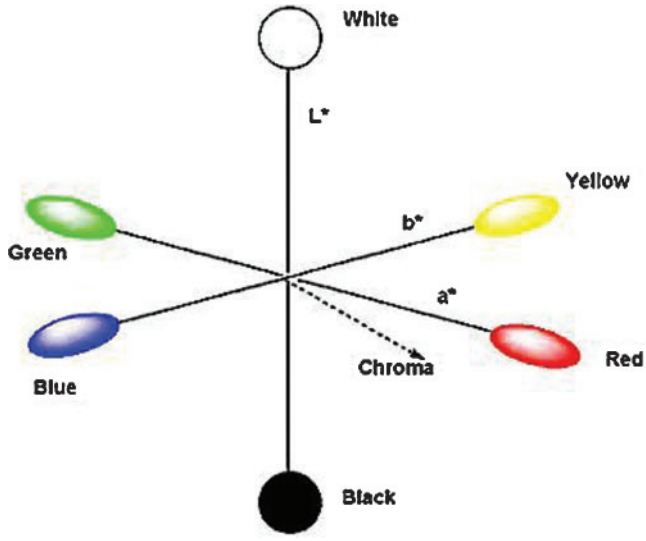

Figure 1 Colour dimensions in CIELAB

Elastomeric samples of different colours were tested before and after 72 h immersion in four different dietary media. The total number of samples tested was 960 (15 different module types × 4 different dietary media × 16 specimens). Square specimens (8 × 8 mm) were cut from the bulk elastomeric stick or ribbon. To ensure blinding and randomization, specimens were number-coded and randomly selected for the tests. They were rinsed with distilled water for 10 s, air-dried for 5 min and initial colour readings taken. A Minolta Chromameter (model CR-221, Minolta Corp., Osaka, Japan) with a probe diameter of 3 mm and white background was used to measure the colour dimensions. Each sample was then placed in a glass container with one of the four media at 37°C and allowed to soak for 72 h. They were then removed, rinsed, air dried and final colour readings taken.

All measurements were done in the internationally standardized CIELAB colour space[23] described below. The advantages of this system for colour measurement is that it more closely represents human sensitivity to colour and equal distances in this system approximately equal perceived colour differences.[17]

The CIE $L^*a^*b^*$ colour space consists of three coordinates L^*, a^*, b^*, as shown in Figure 1. The L^* refers to the lightness coordinate and its value ranges from zero for perfect black to 100 for perfect white. The a^* is the chromaticity coordinate in the red-green axis. Positive a^* values cover the red colour range and negative values indicate green colour range. The b^* is the chromaticity coordinate in the yellow-blue axis.

Positive b^* values cover the yellow colour range and negative values indicate blue colour range.

The changes in the lightness and chromaticity coordinates (ΔL^*, Δa^* and Δb^*) as a result of exposure to diet substances were determined first and the total colour change (ΔE) was also calculated using the relationship:

$$\Delta E = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}$$

where $\Delta L^* = L^*_f - L^*_i$, $\Delta a^* = a^*_f - a^*_i$ and $\Delta b^* = b^*_f - b^*_i$, in which the subscripts f and i represent the final and initial values corresponding to 'after' and 'before' environmental exposures, respectively.

The computed value of ΔE is traditionally used to assess colour changes. Differences of one or two units in ΔE may indicate some perceptible stain. A detailed study by Ruyter *et al.*[18] has shown that a shift in ΔE value of >3.3 reflects a change that is a clinically significant visual discolouration. The ΔE value for each company-colour-media condition subset can therefore be used to assess whether the changes are visually and clinically significant between the subsets. It is also often equally important to understand the relative changes in the individual colour components (i.e. ΔL^*, Δa^*, Δb^*) for a full understanding of the complex changes of colour in elastomeric modules under environmental condition. This study focused on the total colour change ΔE as well as changes in the three individual colour components ΔL^*, Δa^* and Δb^*).

Statistical analysis

Preliminary analyses were carried out to confirm that intra-sample colour differences were minimal. Repeated colour measurements on selected specimens at two time points with a gap of 24 h showed less than 1% variation, indicating high reproducibility in measurements.

Preliminary data from a pilot study was used to determine the sample size. A two-factor design (using four media and clear modules from four different companies) was used in the pilot study. The effect size was determined as 0.217 from the range of group means (1.43) and the within-cell SD (6.60), and the sample size was determined at $\alpha = 0.05$ for a specified 80% minimum power. A sample size, $n = 16$ was selected for the study, and corresponded to $\sim$84% power.

The dependent variables were the calculated values of ΔL^*, Δa^*, Δb^* and ΔE using the measured differences in L^*, a^* and b^* before and after soaking 72 h in media, as described earlier. The independent variables included colour of elastomeric module, company, and type of dietary media. Since different companies marketed modules with different colours, the colours and media effects on modules were tested separately for each company. Consequently, statistical analyses of all treatment comparisons were done using a two-way analysis of variance (ANOVA) at $P = 0.05$ level of significance to examine differences due to the main effects and interactions among these two independent variables in parallel tests for each company. Since the measured and calculated values yielded four sets of data outcomes (namely ΔL^*, Δa^*, Δb^* and ΔE), they were all analysed in parallel two-way ANOVA tests for each outcome, for each of the four companies. Such an analysis focusing on both total colour change and specific changes in individual colour components is useful to understand the nature of the colour degradation. The Tukey-Kramer (HSD) test was also used to show the results of the contrasts of colour and media effects within each company. All analysis was done using SPSS [SPSS, for Windows (v.16), Chicago, IL, USA].

Results

Table 1 is a summary of the two-way ANOVA results with colours and media as dependent variables for each company. In addition to highly significant main effects due to colours and media ($P < 0.0001$) for all companies, the results also reveal statistically highly significant colours*media interaction ($P < 0.0001$) effect. Post hoc contrasts included in Table 1 also reveal that there were significant contrasts in discolouration effects due to individual colour/media differences, as summarized in a decreasing order of discolouration in Table 2. Moreover, the data revealed statistically significant differences in colour degradation between companies Table 3 shows such a contrast for clear modules in the decreasing order Oromco>TP>Unitek>American.

Figure 2 depicts the pattern of total colour change ΔE of modules from American Orthodontics when subjected to different dietary media exposure. The Ruyter criterion of a visually detectable colour change at $\Delta E > 3.3$ is also indicated by the horizontal line. Statistically highly significant colour changes ($P < 0.0001$) were seen for all colours when subjected to spices, coffee and tea. In addition they also represented clinically significant changes as was evident from both Ruyter criteria and visual discolouration in the samples. Cola had a reduced effect on discolouration particularly on grey and green modules, and although statistically significant, no discolouration was visually detected in these samples and the ΔE values were <3.3. Figure 3(a–d) present the overall colour-media interactions as

Table 1 Summary of two-way ANOVA results with module colours and media as independent variables and ΔE as dependent variable for the four companies

Company			*n*	Mean	SD	*P* value	Post hoc†
American	Colours	Blue	64	36.76	27.20	<0.0001	A
		Clear	64	31.83	24.84		C
		Grey	64	9.66	10.57		D
		Green	64	7.32	5.93		E
		White	64	33.35	24.28		B
	Media	Coffee	80	20.30	13.37	<0.0001	B
		Cola	80	2.90	1.91		C
		Spices	80	52.63	25.91		A
		Tea	80	19.30	11.94		B
	Interaction (colours*media)					<0.0001	See Figure 3(a)
Ormco	Colours	Clear	64	45.06	31.32	<0.0001	A
		Grey	64	18.01	12.80		C
		White	64	32.43	17.55		B
	Media	Coffee	48	30.63	12.25	<0.0001	B
		Cola	48	5.62	5.26		C
		Spices	48	62.03	22.16		A
		Tea	48	29.04	11.62		B
	Interaction (colours*media)					<0.0001	See Figure 3(b)
TP	Colours	Blue	64	40.59	23.26	<0.0001	A
		Clear	64	41.50	28.90		A
		Red	64	13.70	9.01		B
	Media	Coffee	48	32.67	13.49	<0.0001	B
		Cola	48	5.81	3.92		D
		Spices	48	62.00	25.40		A
		Tea	48	27.24	12.08		C
	Interaction (colours*media)					<0.0001	See Figure 3(c)
Unitek	Colours	Charcoal	64	22.55	27.51	<0.0001	C
		Clear	64	36.99	34.12		B
		Grey	64	8.07	9.30		D
		White	64	39.01	29.21		A
	Media	Coffee	64	21.41	13.68	<0.0001	B
		Cola	64	2.68	1.67		D
		Spices	64	67.13	27.10		A
		Tea	64	15.40	12.77		C
	Interaction (colours*media)					<0.0001	See Figure 3(d)

†Tukey's Studentized Range (HSD) Tests were used. Means with the same letter are not significantly different. A>B>C>D>E.

Table 2 Summary of Tukey – Kramer tests for colours and dietary media

Total colour change (ΔE^*) in decreasing order of change									
American	Blue	White	Clear	Grey	Green	Spice	Coffee	Tea	Cola
ORMCO	Clear	White	Grey			Spice	Coffee	Tea	Cola
TP	Clear	Blue	Red			Spice	Coffee	Tea	Cola
Unitek	White	Clear	Charcoal	Grey		Spice	Coffee	Tea	Cola
	Most change			Least change		Most change		Least change	

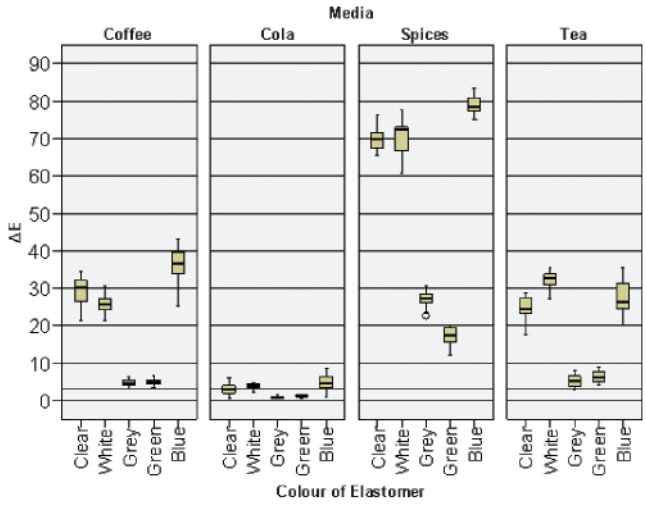

Figure 2 Total colour change (ΔE) of coloured modules from American Orthodontics when subjected to different dietary media. The horizontal line indicates the Ruyter's criterion of 3.3ΔE for clinically detectable total colour change

profile plots for each company, and illustrate that the interactive effects also differ between companies.

The means and standard deviations of the changes in the three individual colour components (ΔL^*, Δa^*, Δb^*) are shown in Table 4, for samples of all colours from all companies after coffee immersion. The values of ΔL^*, which indexes colour on the grey scale, ranged between a minimum of -1.70 and a maximum of -17.37. This range indicates a darkening of the samples over time. The values of a^* varied in the range between -18.00 and $+10.56$, which indicated a trend towards green continuum for most samples except white and green which shifted towards the red. For the b^* value, the samples displayed values within the range from 1.98 to 46.18, which indicates that all the observations were on the yellow side of this colour continuum.

Change in colour components of modules from American Orthodontics immersed in coffee is shown in Figure 4. A highly negative shift of L^* value ($\Delta L^* > -10.0$) for the white coloured modules in coffee was observed. Clinically, it also represented a visual darkening of the grey level. This was also observed to some extent with the clear and blue colours. Neither grey nor green modules were found to have statistically significant ($P > 0.05$) or visually detectable changes in the L^* value.

The white and green coloured modules shifted towards the red side (positive Δa^*) in the red-green axis. In contrast, the blue coloured modules shifted significantly to the more greenish chroma. Clear and grey showed slight changes, which were not considered clinically significant.

The changes in b^* were more dramatic and significant for all colours compared to L^* or a^*. From a clinical perspective, the changes in b^* were visually detectable changes. The samples all became appreciably more yellow regardless of colour. Clear, white and blue showed the most changes and green the least.

Discussion

The results of this study show that significant colour degradation of the elastomeric modules may occur under exposure to dietary beverages and foods in the oral environment, and this is also one of the known clinical shortcomings of elastomeric modules.

Clinically, aesthetics is a significant reason for the selection of coloured modules in orthodontic practice, and staining of elastomeric modules is therefore a major concern for both patients and practitioner. This study identified important criteria to select a module, taking into account the performance profile of the module based on its colour, processing method and brand, as

Table 3 Two-way ANOVA with company and media as independent variables and ΔE dependent variable for clear elastomeric modules

		n	Mean	SD	*P* value	Post hoc†
Company	American	64	31.83	24.84	<0.0001	D
	ORMCO	64	45.06	31.32		A
	TP	64	41.50	28.90		B
	Unitek	64	36.99	34.12		C
Media	Coffee	64	38.16	8.09	<0.0001	B
	Cola	64	3.04	1.28		D
	Spices	64	83.96	8.75		A
	Tea	64	30.21	10.34		C
Interaction (company*media)					<0.0001	

†Tukey's Studentized Range (HSD) Tests were used. Means with the same letter are not significantly different. A>B>C>D.

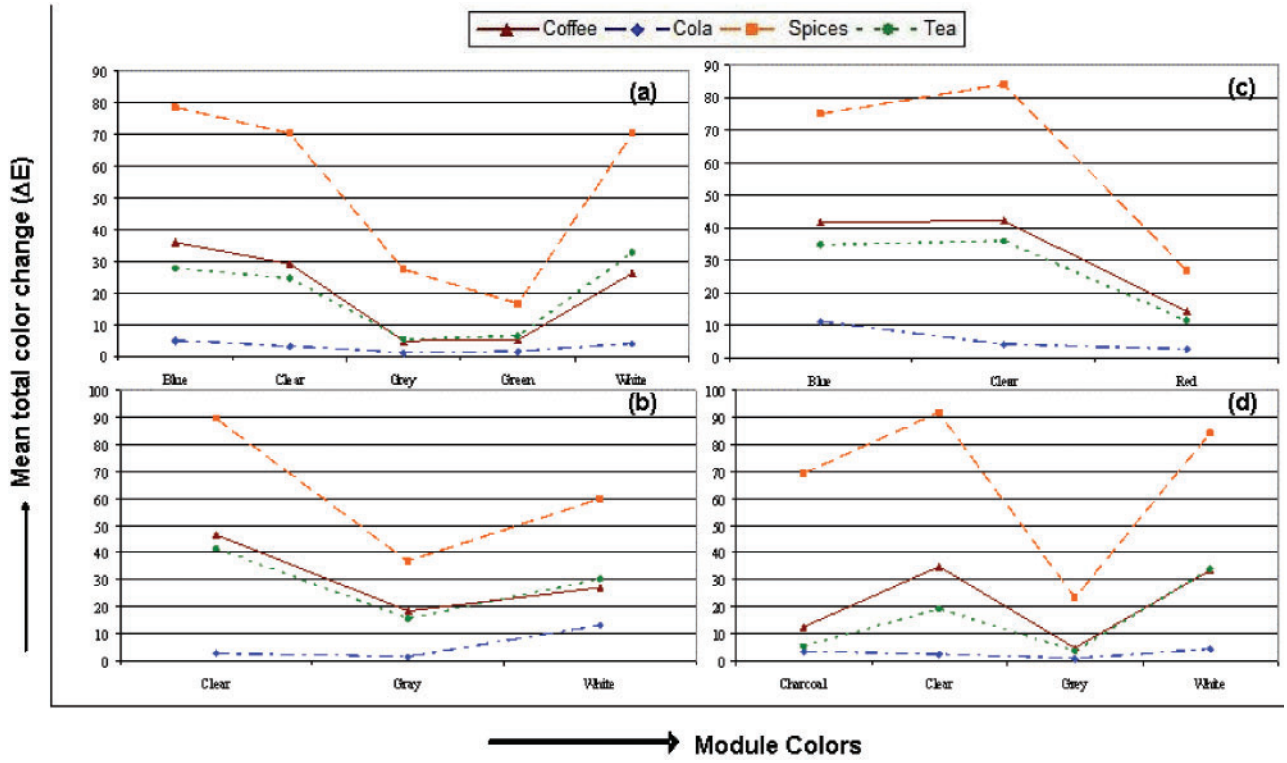

Figure 3 Profile plots of mean total colour change (ΔE) with different combinations of colours and media (a) American, (b) ORMCO, (c) TP, (d) Unitek. Indicates highly significant colours*media interactive effects for all module colours and media

Table 4 Change in colour components values of elastomeric modules of the four companies with coffee as medium

Company/colour	ΔL^*, mean (SD)	Δa^*, mean (SD)	Δb^*, mean (SD)
American			
Clear	−4.28 (2.13)	−1.27 (0.55)	28.85 (4.03)
White	−11.52 (1.62)	4.81 (1.21)	23.16 (2.78)
Grey	−1.73 (0.94)	−0.23 (0.09)	4.52 (1.32)
Green	−2.57 (0.93)	3.61 (1.29)	1.98 (0.69)
Blue	−4.47 (1.13)	−18.00 (1.91)	30.73 (4.75)
Ormco			
Clear	−4.46 (1.24)	−2.44 (0.65)	46.18 (4.10)
White	−17.37 (1.68)	10.56 (1.32)	17.70 (2.48)
Grey	−6.34 (0.99)	−10.52 (1.90)	13.57 (1.72)
TP			
Clear	−7.98 (1.60)	−0.08 (0.90)	41.31 (3.71)
Blue	−8.33 (1.57)	−0.71 (1.79)	40.81 (2.56)
Red	−2.34 (1.35)	−0.74 (1.13)	13.83 (1.59)
Unitek			
Clear	−5.36 (1.31)	−3.43 (0.23)	34.17 (6.33)
White	−13.30 (1.10)	6.53 (1.01)	30.05 (2.27)
Grey	−1.70 (0.33)	−0.32 (0.10)	4.44 (1.32)
Charcoal	−1.89 (2.06)	−1.81 (0.38)	12.14 (3.26)

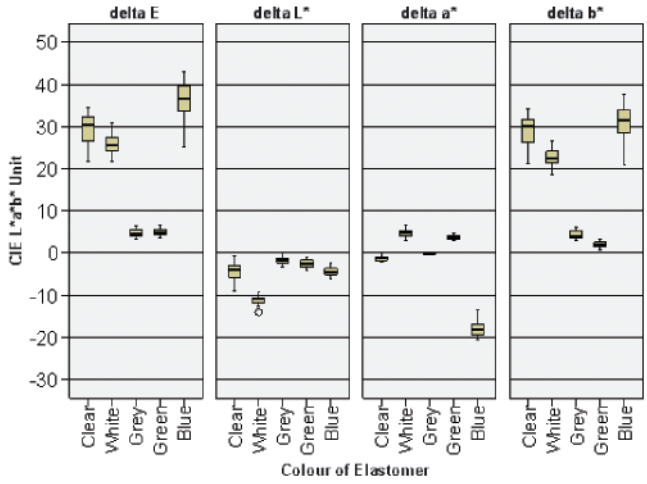

Figure 4 Change in colour components of modules from American Orthodontics when immersed in Coffee. Note that the most significant changes occur in the b^* value, and Δb^* largely contributes to the overall change in total colour (ΔE)

well as the individual's own beverage/spice consumption habits. Clinicians can use such criteria for elastomeric modules for improved aesthetic durability of the modules used in clinical practice.

There are, however, some important limitations of the study that also need to be considered. The elastomeric modules themselves were not used in this study because they are too small for direct colour measurements using the Chromameter. Instead, 8×8 mm square sections were used. Pigment uptake is potentially related to the water uptake, and the resulting swelling of the polymer. The surface area to volume ratio of the samples may strongly influence the water uptake, and the results of this study may not therefore represent the absolute changes in colours of the elastomeric modules; however, we are primarily interested in the relative changes, and the relative changes will be reflected by the ranked differences.

Multiple comparisons were used to detect significant differences in this study. Since the experimental design involved four outcomes with three factors at three to four levels, close to 40 multiple comparisons were involved. Such a large number of multiple comparisons with the same data may increase the chance of a type I error by incorrectly identifying a significant difference where none exists. For this reason, we used visual observations of differences to confirm the most important statistical test outcomes of interest, where possible.

This investigation was an *in vitro* study, and some additional differences with clinical situations must be pointed out. For example, there was no consideration of the surrounding area such as shade of the tooth, metal versus clear brackets, lightening within the mouth that would play a role in the clinical situation. The study did not simulate the role of saliva and oral clearance on slowing down the long term build up of stains in the oral environment. The saliva within the oral cavity functions to dilute the concentration of the ingested beverage. Often saliva can also function as a buffer for the pH of the beverage. Moreover, the study did not address the issue of differences between individuals expected *in vivo*. It has also been shown that *in vivo*, a non-continuous proteinaceous biofilm forms on the surface of the modules.[11] The effect of the dietary media on this biofilm and possible effect on colour was not examined. The concentration of the media would have a definite impact on the staining potential; therefore it is possible that different brands of coffee, tea and cola would have a different effect as would brewing methods. Red wine has been found to be a significant stainant of aesthetic resin restorations.[19] With adult orthodontic patients being possible red wine drinkers this could potentially be an important stainant to examine in future studies. In addition, besides colour, there are other factors that favour choice of elastomeric modules in patients.

A number of factors are known to influence colour stability. The chemical composition and specific details of processing and manufacturing, although proprietary for each of the companies, are important variables. The extrusion/die stamp processed modules (3M/Unitek, ORMCO, TP) typically showed more staining than injection moulded elastomer (American Orthodontics). The synthesis of polyurethane involves multiple steps. The polyurethane is the final product of many chemical reactions involving several compounds. Thus polyurethanes with different chemical profiles can be produced.[2,3] The interaction of their active chemical groups with additives that have been added for processing or filler material for tinting will be different. Chemistry also influences the configuration of the chains of the elastomer and their ability to withstand deterioration from external agents and processing conditions. Processing conditions may also affect the structure and configuration of the polymeric chains. In addition the surface characteristics such as texture, porosity could be different.

Exposure to water, enzymes, chemicals and heat have been shown to have an effect on the structure and glass transition temperature (T_g) of the materials. A difference in T_g is indicative of different molecular configuration and structure. A higher T_g indicates a more rigid polymer due to the presence of more cross-linked type of covalent bonding or larger side chains causing steric interferences. Evangelista *et al.*[14] found that there was significant difference amongst companies of elastomeric

ligatures in tensile load at failure and T_g when exposed to disinfectant solutions. Huget[15] studied the changes in elasticity of orthodontic elastomers when stored in water. He suggested that exposure to water leads first to weakening of noncovalent bonds (intermolecular forces) and concurrent formation of hydrogen bonds between water molecules and macromolecules. The water functions initially as a plasticizer and facilitates slippage of molecules or chain segments past each other. Subsequently there is chemical degradation where polyester urethanes are decomposed by addition of water across ester linkages rather than linkages. This reaction is catalysed by acid, and hence a low pH such as from cola further facilitates this hydrolysis of the polymer. Substances are leached from the polymer over time, and it would be plausible that pigments and other compounds from the beverages and species could penetrate deep into the polymer structure and cause discolouration.

Collection of pigments could also occur on the surface. Textural and morphological changes at the surface may have also contributed to the differences amongst companies. Morphological changes such as surface porosity and roughness are known to adversely affect colour perception due to the fact that the surface texture can significantly modify light scattering effects. Extruded modules may exhibit more porosity due to air entrapment during processing. Microcracks during processing could cause light scattering due to the rough morphology, and further penetration of pigments contributing to greater stain and discolouration of the sample.

The clear elastomers of all the companies consistently showed colour changes that would not be acceptable clinically to adults consuming a lot of spices or coffee and tea, but they were clinically acceptable to patients consuming cola beverages.

From a clinical perspective, this study has demonstrated that coloured and clear orthodontic elastomeric ties are prone to significant change of colour/stain in the oral environment. Clinicians should be aware that colour stability of orthodontic ties will vary between vendors and manufacturing process. Orthodontic patients should be aware that different colour ties will change colour to different degrees. These changes are influenced by the spices in the food and types of beverages they drink. The aesthetic considerations for improved colour stability must therefore play an important role in the selection of coloured elastomeric modules for clinical use.

Conclusions

The following overall conclusions were supported by this study.

- Exposure of clear and coloured elastomeric modules to spices and beverages such as coffee, tea causes significant discolouration *in vitro*.
- The degree of discolouration varies with the original colour of the module. Clear and lighter coloured modules exhibited more change than darker colours.
- Spices and coffee had the most effect and cola the least.
- From an aesthetic point of view, elastomers of darker shades and colours should be preferred and patients should be made aware of the effect of spices in food and coffee on colour change.

Contributor statement

Anil Ardeshna was responsible for the study design, logistic, drafting, critical revision and final approval of the manuscript. TK Vaidyanathan was responsible for technical and scientific support, data interpretation, revision of manuscript and final approval of the manuscript. Walter Novelli was responsible for data collection. Shuying Jiang was responsible for the statistical analysis. Anil Ardeshna is the guarantor.

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