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Measurements and modelling of the influence of dentine colour and enamel on tooth colour

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ABSTRACT

Objectives: We provide a quantitative predictive model for the extent to which coloured dentine, visible through the enamel, contributes to tooth colour. Our model uses (L^*, a^*, b^*) measurements rather than spectral measurements.

Methods: We have used a model system, composed of a slice of bovine enamel placed on top of coloured paper. We have measured the colour of the enamel–paper combination, as an analogue for a tooth, and have related this to the colour of the paper, as an analogue for dentine. By changing the paper colour, we have been able to explore how the colour of dentine determines tooth colour, according to our model system. We have also compared hydrated and desiccated samples.

Results: In qualitative terms, superimposing the enamel on top of the paper increases the ‘‘lightness’’ for all colours tested except white while simultaneously reducing the chromaticity, a measure of the extent to which the colour differs from grey. Desiccated enamel is much more effective at increasing the lightness and reducing the chromaticity than hydrated enamel. Quantitatively, our measurements are reproduced by the mathematical model we have developed to within 2% in ‘‘lightness’’ and about 8% in chromaticity.

Conclusions: We are able to predict the colour of an analogue for a tooth, composed of bovine enamel and coloured paper, from the colour of an analogue for the dentine, the coloured paper alone, with good accuracy. This understanding provides insights into the role of dentine colour in determining tooth colour.

Clinical Significance: Our work helps quantify the importance of dentine colour, compared to other, extrinsic causes of colour, such as staining, in determining the visible colour of teeth. Our predicted colours represent a baseline to which extrinsic sources will add.

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1. Introduction

There are many potential causes of tooth discolouration, including extrinsic causes such as surface staining and enamel discoloration through smoking or drinking tea, coffee or wine, and intrinsic causes such as a degradation in the colour of the dentine which is visible externally through the enamel.[1,2,3] Some of these discoloration mechanisms are short term and reversible with suitable cleaning.[4] However, other causes are semi-permanent, reversible only through tooth bleaching procedures using, for example, carbamide peroxide and commonly known as tooth whitening.[5,6] This paper focuses on the role of dentine colour in determining tooth colour. We are

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able to predict tooth colour due to dentine colour alone, with both colours measured using simple colourimeter measurements such as (L^*, a^*, b^*), rather than full spectral measurements. This predicted tooth colour represents a baseline to which extrinsic causes of discolouration will add. As the extent of discolouration due to the latter cannot easily be quantified, we cannot fully resolve the debate over the importance of dentine colour in the overall appearance of human dentition. However, our baseline colour predictions should allow practitioners and researchers to develop an understanding of the relative importance of intrinsic and extrinsic colouration sources in that overall appearance.

Enamel is a translucent scattering medium which, at the thicknesses present in human teeth, does not fully obscure the colour of the underlying dentine. For example, an in vitro study of the colour of 28 teeth from different patients showed strong correlation with dentine colour when the overlying enamel was removed.[7] Degradation in the colour of dentine, for example with age, can therefore lead to tooth discolouration.[8,9] This is exacerbated when thinning of the enamel takes place or when gum recession occurs, thereby exposing tooth surface closer to the cementoenamel junction and hence covered in thinner enamel.[7] An extreme example of the role of dentine colour occurs when blood escapes from the blood vessels in the tooth and perfuses the dentine, leading to severe discolouration of the dentine. Here, the external appearance of the tooth is also considerably darkened. In order to understand these effects, a theoretical model, able to predict tooth colour from dentine colour and enamel characteristics, is desirable. However, such a model faces three challenges, two theoretical and one practical. Firstly, it is necessary to identify a model for the wavelength dependent scattering of light in the enamel and hence be able to predict the spectrum of light emerging from the enamel-dentine combination from that emerging from the dentine alone. Secondly, it is necessary to relate those spectra to the colour perceived by the human visual system, with its associated complexities. Finally, for practical application, it is necessary to recognise that the measurement of spectral reflectivities using a spectrophotometer, whilst possible in the laboratory, is unlikely in the dental surgery/office and that the terminology used in optical physics is alien to clinical dentistry. A more straightforward measurement, using the colourimeters already in routine use in the surgery/office, is to be preferred. Our work addresses all three challenges.

O'Brien et al.[10] tackled the first two challenges using a model system composed of dental porcelain to represent the enamel and coloured opaque backing layers to represent the dentine. They used the so-called two flux model of Kubelka and Munk[11] (K-M model) to represent scattering in the porcelain but measured the full reflectance spectra for both the porcelain and the backing layers using a spectrophotometer. They then compared the measured and predicted CIE colour parameters of luminous reflectance, dominant wavelength and excitation purity.[12] However, as noted above, measuring these spectra is impractical in the dental surgery/office and inferring it from measured $L^*a^*b^*$ values is impossible due to the weighted averaging used to derive these values. Fortunately, the colour saturation levels typically exhibited by human dentine and enamel are sufficiently low that an approximation[13] can be used to relate directly the $L^*a^*b^*$ values for a coloured surface such as dentine to the equivalent values when the coloured surface is covered by a scattering layer such as enamel.

The aim of our work is to show that it is possible to predict tooth colour measured directly with a colourimeter from equivalent measurements on the dentine, without the need for full spectral measurements, by combining a physical model for light scattering, a means of predicting perceived colour and a mathematical approximation method. We also use a model system, like that of O'Brien et al., but with a slice of bovine enamel as the scattering layer and coloured paper as the backing. The paper is an analogue for the dentine while its combination with the bovine enamel is an analogue for a tooth. Using a wide range of paper colours, whilst keeping the enamel slice the same, we have been able to measure the influence of the colour of the dentine analogue on the colour of the tooth analogue. This model system has a very abrupt boundary between enamel and dentine. Fortunately, this is also the situation for human teeth.[14] In Section 2, we describe our sample preparation and measurement method while, in Section 3, we summarise the key results of our theoretical analysis.[13] In Section 4, we present our comparison between the measured $L^*a^*b^*$ values for the dentine analogue and the tooth analogue and the calculated $L^*a^*b^*$ values for the tooth analogue based on our theoretical work. Sections 5 and 6 discuss the results and present conclusions.

2. Materials and methods

A bovine tooth was provided by the Academic Centre for Dentistry (ACTA), Amsterdam. A section of enamel was cut from the labial surface of the tooth, which had been previously bleached for 50 min using 23% carbamide peroxide in a proprietary preparation to minimise the effect of enamel colour, using a mechanical microtome at a depth of 3–4 mm from the surface. The section was then thinned to about 1 mm, chosen to represent the thickest enamel typically observed in human teeth. A thinner slice would have been desirable but was judged to be mechanically too fragile to prepare. The cut surface was then polished using silicon carbide grits of diminishing size, then 6 μm water-based diamond suspension using a short-nap polishing cloth and finally 1 μm water-based diamond suspension. The other surface was the natural surface of the tooth and hence was curved. Over the measurement area, the thickness of enamel varied from 1 mm at the centre to 0.7 mm at the edge. This single enamel section was used in all the measurements of the tooth analogue.

Our coloured backing layers, used as the dentine analogue, were prepared using Microsoft Word's colour palette to determine the RGB colour and then printed in 4 cm × 4 cm squares on heavy weight gloss photo paper using a laser jet printer set to high quality mode. Gloss paper was used as it is largely colour safe when wet, a necessary feature as we wish to compare both desiccated and hydrated tooth analogues. For measurements when desiccated, the printed paper was used "as is", direct from the printer, while the enamel was dried by storing overnight in a ventilated incubator at 37 °C. For hydrated analogues, both enamel and paper were hydrated as follows: the enamel was stored overnight in deionised

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