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ORIGINAL ARTICLE

Anisotropic local physical properties of human dental enamel in comparison to properties of some common dental filling materials

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Abstract

Objective. A major aspect in evaluating the quality of dental materials is their physical properties. Their properties should be a best fit of the ones of dental hard tissues. Manufacturers give data sheets for each material. The properties listed are characterized by a specific value. This assumes (but does not prove) that there is no direction dependence of the properties. However, dental enamel has direction-dependent properties which additionally vary with location in the tooth. The aim of this paper is to show the local direction dependence of physical properties like the elastic modulus or the thermal expansion in dental hard tissues. With this knowledge the 'perfect filling/dental material' could be characterized. ***Materials and method.*** Enamel sections of ~400–500 μm thickness have been cut with a diamond saw from labial/buccal to palatal/lingual (canine, premolar and molar) and parallel to labial (incisor). Crystallite arrangements have been measured in over 400 data points on all types of teeth with x-ray scattering techniques, known from materials science. ***Results.*** X-ray scattering measurements show impressively that dental enamel has a strong direction dependence of its physical properties which also varies with location within the tooth. Dental materials possess only little or no property direction dependence. Therefore, a mismatch was found between enamel and dental materials properties. ***Conclusion.*** Since dental materials should possess equal (direction depending) properties, worthwhile properties could be characterized by transferring the directional properties of enamel into a property 'wish list' which future dental materials should fulfil. Hereby the 'perfect dental material' can be characterized.

Key Words: *dental enamel, dental material, elastic modulus, thermal expansion, direction dependence*

Introduction

Different classes of dental materials exist. There are composites, glass ionomer cements, plastic materials, framework and veneering ceramics, dental metals, dental alloys, etc. The physical properties of these material classes are of high interest for dentists. Their properties play an important role 'for choosing the right material' for a given task. Dental materials do also promise to be long lasting, have comparable physical properties like elastic modulus or thermal expansion to dental enamel or to look like enamel itself. These promises are very interesting and commendable. Durability and aesthetics of these materials can be easily checked in contrast to the comparability of physical properties to those of enamel. To validate the comparability, one must first know the properties of enamel itself in detail. Therefore, usually the measured values of elastic modulus, e.g. by indentation [1–4], are compared. Thereby it is assumed that the value of the property is the same in all directions for the dental material as well as for dental enamel. Mostly overall bulk values are compared. In detail, however, one will realize that, for most polycrystalline materials, there is a direction dependence of the value of the property [5,6]. This direction dependence is based upon the orientations of the crystallites a material is made of [7]. Since the orientations may also change with location, e.g. in dental enamel with the change of orientation of the enamel prisms depending

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on location within the tooth [8–11], this opens a complex scenario. The aim of this paper is, therefore, to show the local direction dependence of physical properties like the elastic modulus or the thermal expansion in dental hard tissues. Furthermore, with this knowledge, a hypothetical 'perfect future dental filling' and its properties is described as an example.

Materials and methods

Materials

A total of over 400 data points on all types of teeth (with an intact anatomic corona without any defect or dysplasia) were measured. The teeth were used originally for another study, approved by the local ethics committee (University of Goettingen, issue no. 16/09/09 from 20.07.2009). The teeth were cleaned and stored dry for immediate analysis. For detailed x-ray scattering measurements, sections of ~400–500 μm thickness have been cut with a diamond saw from labial/buccal to palatal/lingual (canine, premolar and molar) and parallel to labial (incisor). For all data-points, 3-dimensional direction-dependent values for the elastic modulus and the thermal expansion of human dental enamel were measured, and calculated using the procedure described below.

Method

Normally dental scientists use X-rays mainly for creating absorption images (reflecting differences in density). Here the authors use X-ray scattering techniques [12] which reveal information about the crystal structure, atomic building principles, chemical composition and physical properties of crystalline materials. These techniques are well established in material science and are based on observing the scattered intensity of an X-ray beam hitting a sample as a function of incident and scattered angle, sample orientation as well as wavelength. Especially synchrotron transmission step measurements (with hard X-rays) are used to evaluate the orientation of crystallites within the 'scanned' sample volume [10,11,13,14]. Knowing the orientation of the crystallites in detail is the basis for calculating 3-dimensional direction-dependent physical properties [5–7]. Most times, physical properties are treated as overall bulk values. As the single crystallites which make up a polycrystalline material like dental ceramics possess direction-depending property values [7], it mainly depends on the orientations of the many small crystallites and their interaction, which macroscopic property value is observed in a specific direction [6]. Hereby the different direction-dependent property values of the crystallites can be cancelled out by each other if the crystallites are distributed randomly. This, a random orientation distribution, is most times not the case for a polycrystalline material. Due to the processing of materials there are nearly always preferred orientations; in dental ceramics, e.g. by casting or pre-sintering, or in dental enamel, e.g. because of the hierarchical structure [15]. Characterizing crystallite orientations with x-ray scattering techniques, one can weigh these orientations with the single crystal direction-dependent properties (given by single crystal tensors) to get macroscopic direction-dependent properties [13]. In this manner, 3-dimensional property values are calculated in this paper.

The quality of the method and of the results is shown in comparison with values from indentation measurements (only for one direction) and with results from other research groups [16].

Representing 3-dimensional, directional data (the stereographic projection)

Plotting 3-dimensional, directional data in a 2-dimensional diagram is not trivial. A smart way of presenting this data is using the stereographic projection (most probably invented by Hipparchos, Greek astronomer, 190 BC–120 BC) [17]. The construction of this projection can be seen in Figure 1 and is described in the figure caption in detail.

Results

For the comparison of the results a short literature review has been done, compiling average physical properties for the different dental material classes (from manufacturers data sheets). A compilation of the results can be seen in Table I.

In contrast to these overall bulk properties, the dental materials do have direction-dependent properties (due to their processing) as a totally random crystallite distribution is very rare. The preferred orientation of crystallites (as in dental enamel [9,10]) leads to direction-dependent property values [4,13]. The orientation of enamel crystallites can be sufficiently described by the orientation of the (001) crystal lattice plane (cf. Figure 2) since the crystallites are oriented in a fibre texture [8].

This special arrangement leads to direction-dependent properties, as shown in Figure 3. With the possibility to get the orientation of the crystallites and also with the direction dependence of important physical properties like elastic modulus or thermal expansion, one can even get a 'local map of direction dependence' for a property. Therefore, a tooth was measured in a data grid with a small step size (Figure 4).

Looking at Figure 4 in detail one can see that there is a strong direction-dependence of the elastic modulus and that the orientations of the maximum values also depend on the location within the tooth. From minimum values (137 GPa) to maximum values

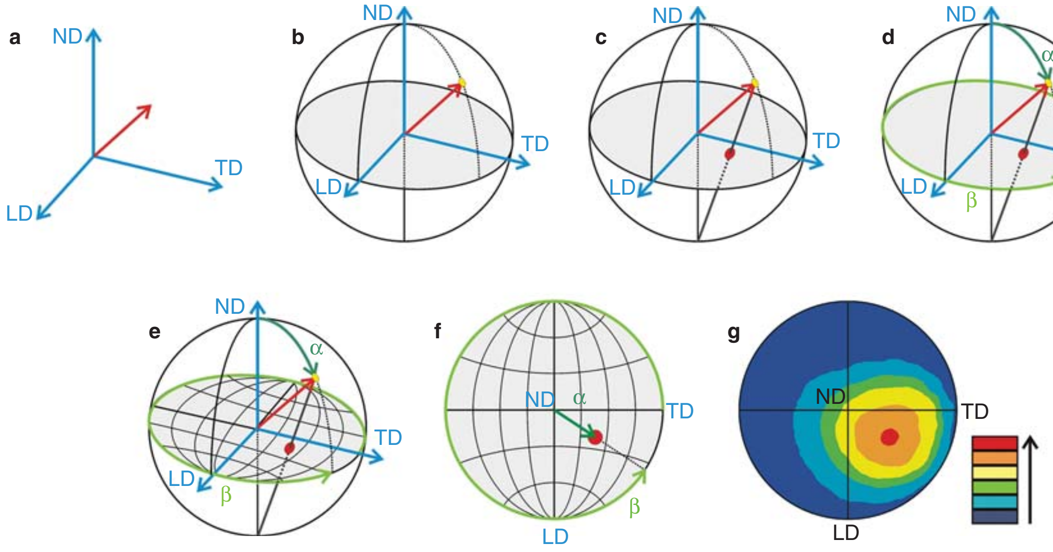

Figure 1. Construction of the stereographic projection. An arbitrary direction (red arrow, A) is defined in the (sample) co-ordinate system, which is spanned by normal direction (ND), longitudinal direction (LD) and transversal direction (TD). Then an imaginary sphere is created around the sample. The intersection of the direction coming from the middle of the sphere with the upper hemisphere itself is memorized (yellow dot, B). This intersection is then connected with a direct line to the lower hemisphere's pole. The intersection of this line with the equatorial plane is then marked as a pole for this direction (red dot, C). With this procedure all possible 3-dimensional directions can be plotted. A specific direction is hereby characterized by the angular pair α and β. α is running from the normal direction to the equatorial plane ($0^\circ \le \alpha \le 90^\circ$). B is running in the equatorial plane ($0^\circ \le \beta \le 360^\circ$) (D). Now concentrating only on the equatorial plane, one can take this plane out of the construction and look at it from above (E and F). Doing so, one has the possibility to draw and characterize all 3-dimensional directions in this 2-dimensional plot which is called a *stereographic projection*. If more than one direction should be plotted, respectively the frequency of occurrence of all possible directions, the stereographic projection is colour coded [G]. If, in this manner, e.g. the thermal expansion is plotted, one can read part (G) in this way, that highest values of expansion can be found in directions marked with red, lower values in directions marked with orange, etc.

(157 GPa) there is an increase of ~ +15%. Surprisingly absolute maximum values (darkest red) were not found at the outer side of enamel, where contact to the opposite tooth takes place, but in the middle depth region of enamel at the cusps (Figure 4, black ellipses).

In the same way, one can create a local map for the anisotropy of the thermal expansion, which can be seen in Figure 5. Figure 5 shows impressively that dental enamel has a strong direction dependence of the thermal expansion. Looking at a single data point, values range from ~18 up to $22.7{*}10^{6}/^{\circ}\mathrm{C}$, which is an increase of ~ +26% from minimum to maximum value. Additionally the orientation of this behaviour is also location-dependent.

Table I. Compilation of typical physical bulk properties for different dental material classes.

Dental material class	(overall) Elastic modulus [GPa]	(overall) Thermal expansion [$10^{6}/^{\circ}$C]
Composites	~16	~27
Glass ionomer cements	~20	~13
Framework ceramics	~80	~10
Dental metals/alloys	~220	~15

Discussion

Today's dental materials are specified by the manufacturers only by giving overall bulk physical property values (as exemplary shown in Table I). Since most crystalline materials possess a preferred orientation of their compounds, it is logical that they should also have direction-dependent properties. This feature is of great importance because dental enamel also possesses strongly direction-dependent properties (cf. Figures 4 and 5). Even if dental materials would have no preferred orientation of their crystalline compounds and thereby have no direction-dependent properties, as the manufacturers claim by giving only overall bulk values, this would not match with the properties of dental enamel itself (since it has a strong direction-dependence in its properties). This

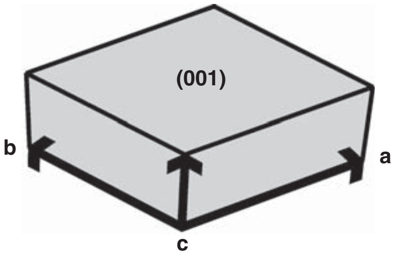

Figure 2. Schematic drawing of the crystallographic unit cell of hydroxylapatite with marked lattice plane (001).

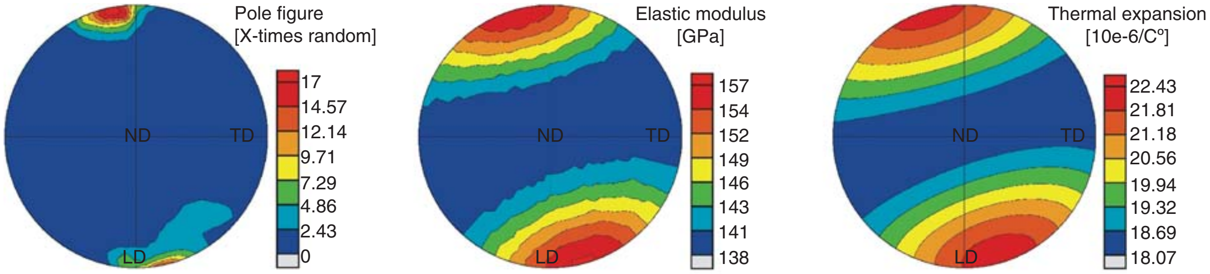

Figure 3. Exemplary stereographic projections. On the left side the distribution of the (001) crystal lattice plane in the sample co-ordinate system (span by ND, TD, LD) can be seen. In the middle, the corresponding direction-dependent elastic modulus is drawn (in the same co-ordinate system). On the right side, the direction-dependence of the thermal expansion is plotted. All data in this figure corresponds to the data point number 14, shown in Figure 4 or Figure 5.

matching of the (direction depending) physical property values is essentially needed to make sure that dental materials will last long and do not introduce a danger to healthy enamel (e.g. by being too hard [caused by high elastic modulus] and therefore facilitating abrasion on the opposite tooth or by differing in thermal expansion and therefore create extension or compression forces in the tooth). To make all of this even more complex, the direction dependence of dental enamel properties also varies with location within a tooth. The difference between absolute minimum and maximum values for the elastic modulus is ~ +15% and for the thermal expansion ~ +26%.

Comparing the results of typical physical bulk properties for different dental material classes with the directional properties of enamel, one can say that no class fits in the elastic modulus values well. Some have too low values, some have too high values. Looking at the thermal expansion, the values correspond more to those of dental enamel. Typical composite materials and dental alloys match best their overall bulk values with the ones of dental enamel.

Good dental materials properties should best match the properties of dental hard tissues. By measuring the orientations of dental enamel crystallites and calculating the direction-dependent properties, one can obtain detailed information about the properties which dental material should possess. It is important to mention that the direction-dependence of a property in enamel is also location-dependent. This leads to a picture of a perfect dental material, which is optimized in its directional properties and so coincides with enamel properties perfectly. In contrast to that 'wish' it may not be possible to always have matching properties, because that would mean that one should have not only the right material but one must also insert that material in the right orientation into the tooth. Making compromises, dental materials

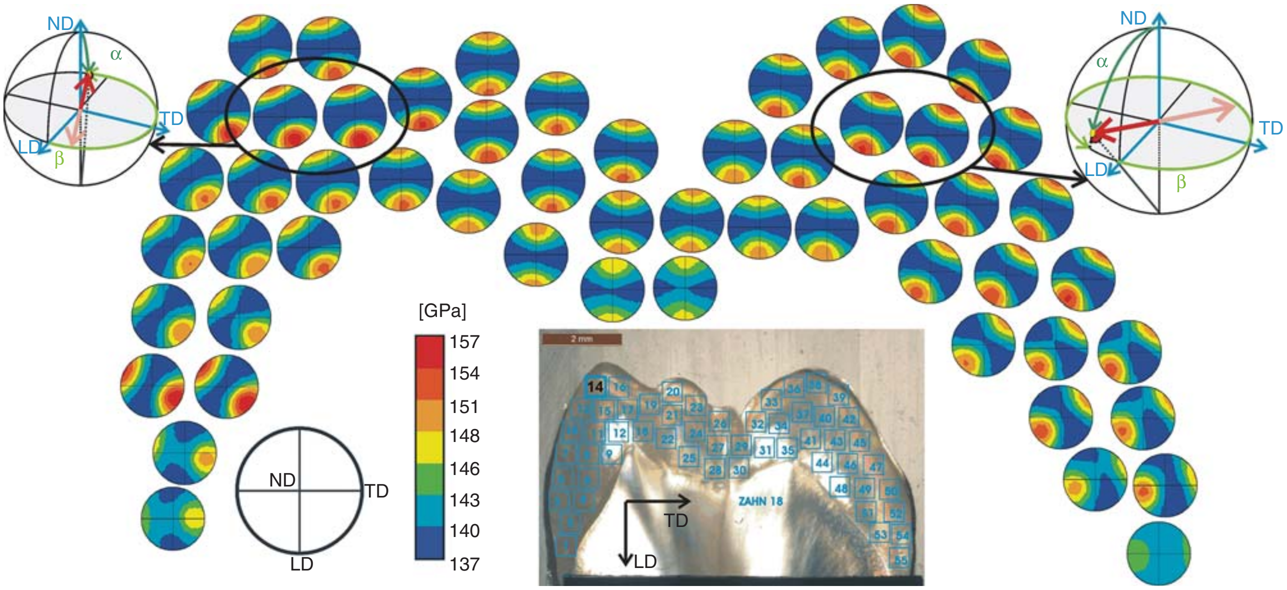

Figure 4. Local map of the direction-dependence of the elastic modulus for a molar tooth (FDI 18) with equal scaling. The sample can be seen in the middle. The co-ordinate system is given by ND (normal direction), LD (longitudinal direction) and TD (transversal direction). Orientations of maximum values of the stereographic projections in the black ellipses are also illustrated by 3-dimensional drawings on the left and right side.

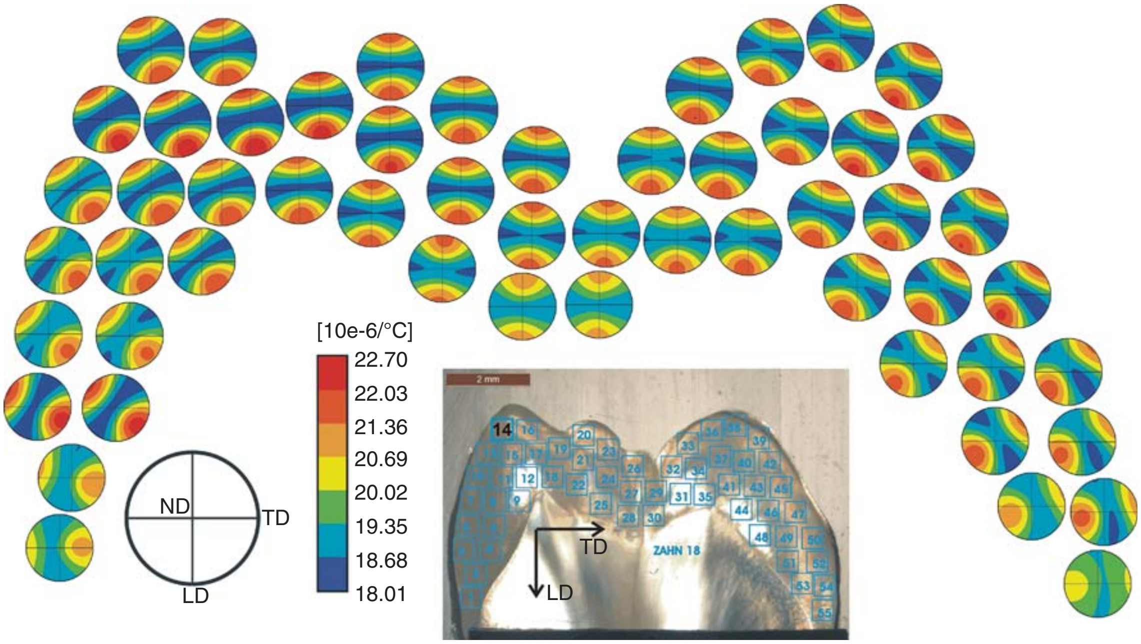

Figure 5. Local map of the direction-dependence of the thermal expansion for a molar tooth (FDI 18) with equal scaling. The sample can be seen in the middle. The co-ordinate system is given by ND (normal direction), LD (longitudinal direction) and TD (transversal direction). Directions are presented by the stereographic projection.

properties should at least lie in the range of dental enamel properties. If these dental materials have direction-dependent properties, these properties should not be in disparity to the ones of dental enamel in the desired location (e.g. their maximum thermal expansion should not lie in the direction of minimum thermal expansion of dental enamel).

There are different methods for characterizing physical properties of dental materials available, but most methods only give property values for a specific testing direction. Indentation methods, for example [1–4], are widely used and highly developed. Nevertheless, indentation methods do not give values for the full 3-dimensional direction dependence of a property, since one would have to test all possible directions, each with a separate indentation measurement. Normally one-to-three specific directions are tested. For all the other possible directions one cannot give reliable values (without testing them). A full, 3-dimensional description of the direction dependence can only be given by x-ray scattering techniques in combination with orientation and property calculations as done in this paper. It would be advantageous if dental material manufacturers would check the real 3-dimensional direction-dependence of physical properties of their products and add this information to their product specifications. Maybe it will be even possible to 'adjust (due to the production process)' crystal orientations of common dental material so that their properties would match those of hard dental tissues better. One possibility to reach this aim could be to check the manufacturing and later on insertion process itself since these parameters can be changed easily and immediately (and are known to influence orientations of crystallites).

If one would like to really evaluate common dental materials in their ability to match with the properties of dental hard tissue, it would be composites or dental alloys which fit best (not regarding their colour and translucency).

There is still a lot of work to be done, getting dental materials with perfect matching properties, but the first step is done here. Physical properties and their direction dependence can be characterized in detail for any location within all types of teeth, which is a basic condition for creating new and better adapted materials.

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