THE EFFECT OF X-RAY RADIATION ON HUMAN DENTAL TISSUE MEASURED BY NANOINDENTATION

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Abstract: The effect of low and high photon energy on the mechanical properties of human dental tissue is investigated by nanoindentation. In principle the trend of hardness and elastic modulus in dentine as well as in enamel show a similar diminution depending on the x-ray dose, but the decreasing of the mechanical parameters at irradiation with higher energy is more pronounced. At both energies at about 3 Gy constant values are achieved. The cumulation of the doses will not affect the mechanical properties anymore.

Introduction

The general practice of the tumor therapeutic irradiation is radiation with high x-ray energy with doses up to 60 Gy. As a side effect teeth destruction will be observed. The aim of this study is to compare the effect of low and high photon energy on the mechanical properties of human dental tissue, enamel and dentine. The idea for this was born by a recent study about the interaction of radiation and bone tissue [1]. The mechanical parameters hardness and elastic modulus were measured by Nanoindentation.

Methods and Materials

10 freshly extracted retained third molars, which had been stored in physiological sodium chloride solution (0.9% NaCl) at 6°C, were used. The solution was renewed every 2 days. The suitability of the physiological sodium chloride solution as a storage medium of dentine samples is proven in the literature [2, 3, 4]. After cutting the teeth in half using a diamond-coated band saw under continuous water cooling (Exakt - Trennschleifsystem Makro, Exakt Apparatebau, Norderstedt, Germany) the pulps were taken away. The separation planes of the halfs were ground with successively decreasing grain size (1200, 2400, 4800; Exakt-Mikroschleifsystem, Exakt Apparatebau, Norderstedt, Germany) under continuous water cooling and finally polished (λtech, England) with a hard synthetic tissue (MD-Dur, Struers), ethylenglycol suspension and diamond spray (grain size 1 and 0,25 µm, DP-Spray P, Struers) as an abrasive. This procedure ensured optimal surface flatness. On each tooth half a 2 x 2 mm^2 region of interest (ROI) was marked in enamel and dentine, whereas the ROI at the second half is opposite at the same place. As result we have two groups each with 10 halves teeth.

The low energy irradiation has been carried out with an x ray generator RT250 (Philips, Eindhoven, Netherland; U = 125 kV, I = 20 mA, filter: 0,2 mm Cu) and the high energy irradiation with an accelerator (SIEMENS Mevatron MD2; U = 6 MV). The teeth were exposed to increasing doses.

The hardness and the elastic modulus of enamel and dentine are determined before and after exposing to x-ray radiation at each dose.

The NanoindenterII (MTS Systems Co., Oak Ridge, TN) was used for measuring the mechanical parameters with a Berkovich diamond indenter, in load control testing at constant room temperature (~21 °C) and ambient conditions. The indenter was loaded and unloaded with a constant loading rate. A constant load hold period, 100 sec at 10% of the maximum load, was inserted to correct the displacement data for thermal drift. The tests were conducted to a maximum load of 1 mN. 12 indents at every tooth half were performed in each ROI in dependence of the dose.

The values of the hardness, H, and of the elastic modulus, E, were determined by using the well known method of Oliver and Pharr [5]. The contact stiffness S was calculated from the linear slope of the unload-displacement curve:

$$S = \left.\frac{dF}{dh}\right|_{F=F_{\max}} \qquad (2)$$

The contact depth h_c at the peak load F_{max} is:

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$$h_c = h_{\max} - \varepsilon \frac{F_{\max}}{S}, \quad (3)$$

where ε is a constant, that depends on the geometry. In this case $\varepsilon = 0.75$ was used. The projected contact area A_{cp} for a perfect Berkovich indenter tip is:

$$A_{cp} = 24.5 \cdot h_c^2 \quad (4)$$

In fact the contact area is a function of the indentation depth because of the deflection of the reality from the ideality. But if the aim is to find out relative changes of the properties, it is suitable to calculate with equ. (3), as it was done in this work.
The relation between S, A_c and the elastic parameters of sample and indenter is:

$$S = \frac{2}{\sqrt{\pi}} \beta \sqrt{A_c} \cdot \left(\frac{1-\nu_S^2}{E_S} - \frac{1-\nu_i^2}{E_i} \right)^{-1}, \quad (5)$$

where $\beta = 1.0226$ is the correction factor for a Berkovich indenter and ν is the Poisson ratio, respectively. The subscripts s and i correspond to the sample and the indenter. For the diamond indenter $E_i = 1141$ GPa and $\nu_i = 0.07$. The Poisson ratios in enamel and dentine were assumed to be 0.35. It has been hypothesized by several authors that the prediction error of E_s associated with a variation of ν in a range from 0.2 to 0.4 is less than 10 % [6, 7].
The hardness values H are calculated using the equation

$$H = \frac{F_{\max}}{A_c} \quad (6)$$

where A_c is the area of the indent calculated from the plastic depth of the indent. Because this hardness is based on the contact area under load, it deviates from the conventional hardness determined after unloading. In this case often an elastic recovery is observed.

To exclude any effect of the saline solution on the results, reference teeth were stored in this solution only and the mechanical parameters were measured from time to time.

Results

Firstly, during the period of the investigation, no influence of the storage solution could be detected. Figures 1 and 2 illustrate the mechanical parameters as function of the storage time in physiological sodium chloride solution in the typical period of irradiation. A statistical analysis (t-Test) of the values with assumption of a level of significance of 0.05 shows that the hardness of dentine and enamel are not different (p = 0.76 and 0.79, respectively) to the origin values after six weeks. Also no significant differences in the elastic modulus could be found (p = 0.95 for dentine and p = and 0.84 for enamel).

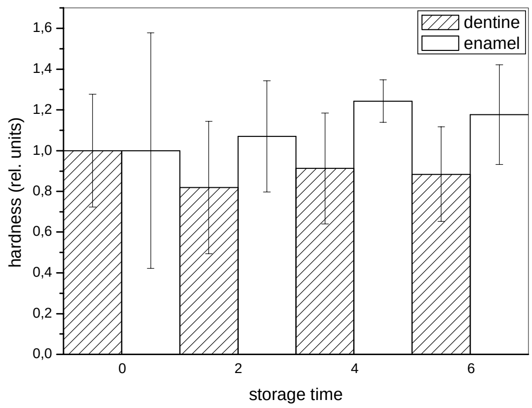

Figure 1: Hardness values vs. storage time of the teeth in physiological sodium chloride solution (0.9% NaCl) at 6°C

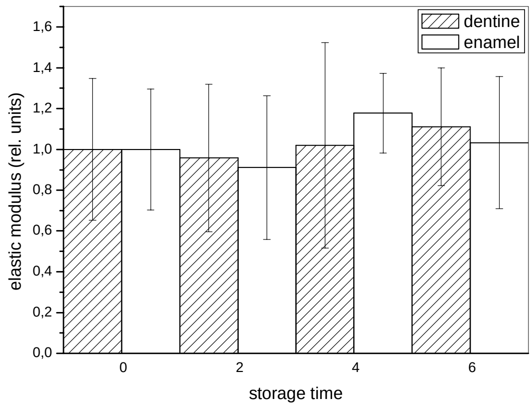

Figure 2: Elastic modulus values vs. storage time of the teeth in physiological sodium chloride solution (0.9% NaCl) at 6°C

So, the used storage medium, physiological sodium chloride solution, does not affect the mechanical parameters.

According to the first result that there is no influence by the storage medium, the further results are only determined by the influence of x-ray radiation on the teeth tissue. In principle the trend of hardness and elastic modulus in dentine as well as in enamel show a similar decreasing behaviour depending on the x-ray doses (Fig. 3-6).

At high energy radiation we find a dramatically decrease of the mechanical parameters after 0.5 Gy yet. The hardness is reduced about 73% for enamel and 55% for dentine and just as the elastic modulus about 60% for enamel and 45% for dentine. Usually the therapeutic irradiation starts with a dose of 2 Gy but the enamel is nearly complete damaged then. Further doses have hardly an additional effect. It seems that a limiting value is approached. In principle dentine shows the same behaviour, but we find an additional effect between 3...10 Gy. Here the values have a soft increasing like a radiation hardening. This reproducible effect must be investigated separately. After 10 Gy the mechanical parameters approach the same values as before at 2 Gy and a limiting value is achieved.

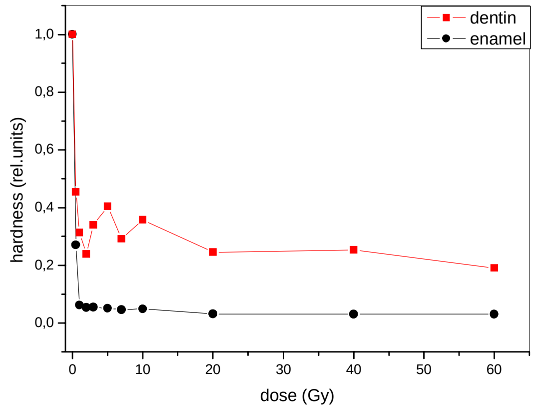

Figure 3: Hardness of enamel and dentine vs. doses after high energy radiation

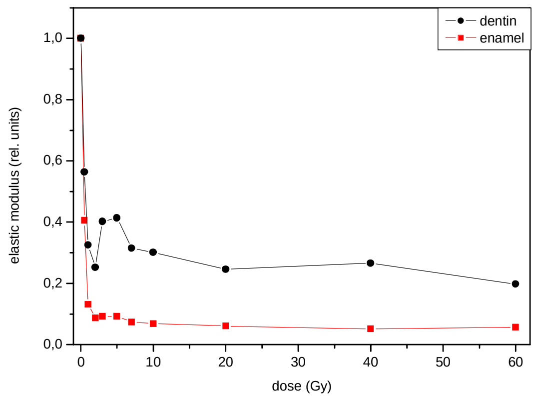

Figure 4: The elastic modulus of enamel and dentine vs. doses after high energy radiation

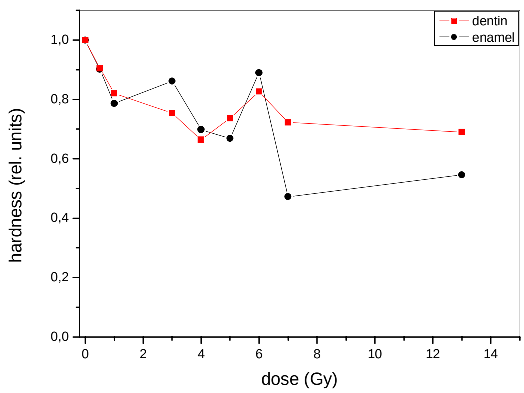

Figure 5: The hardness of enamel and dentine vs. doses after low energy radiation

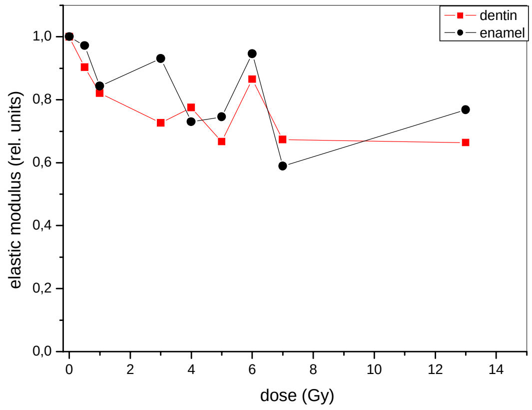

Figure 6: The elastic modulus of enamel and dentine vs. doses after low energy radiation

At low energy radiation the hardness and elastic modulus in enamel and dentin decrease also, generally to approximately 80% of the initial value at a dose of 2 Gy. With increasing doses the decrease of the mechanical parameters achieve at 10 Gy a nearly constant level of 60% of the initial value. Also a limiting value is approached.

I.e., also after the effect of x-ray with lower energy than it is used for the tumor therapeutic irradiation in the head neck region, hardness and elastic modulus from tooth hard substances decrease important.

Discussion and Conclusion

The investigation of dental tissue after irradiation shows that radiation with low energy and low doses change the mechanical properties important, too. The explanation for these changes can be given by the decarboxylation of the tissue. The organic matrix interacts with the apatite crystals via calcium ions from electrostatic binding of collagen side chains carboxylate and surface mineral phosphate groups. The irradiation promotes side chain decarboxylation and a loss of acidic phosphate groups with formation of new calcium ion bridged phosphate groups. The mineral-organic interaction is reduced [8]. The short increase of the mechanical values at doses between 3 Gy and 10 Gy may be explained by removal of calcium mediated electrostatic bindings of the collagen side chain carboxylate groups to apatite phosphate groups [8]. The decarboxylation demands sufficient high excitation energy. At high x-ray energy the overcoming of the binding energy is more probable. As consequence, the decrease of the mechanical parameter is stronger here than at the low energy irradiation.

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