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Alternative Methodology for Flexural Strength Testing in Natural Teeth

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The use of natural teeth for performing *in vivo*, *in situ* and/or *in vitro* studies has been widely observed in the dental field. The mechanical behavior of teeth subjected to masticatory efforts is commonly used as a variable of response. In conditions of malocclusion, the most relevant component accounting for the integrity of the dental structure is non-axial (flexural). This force, while acting on a tooth in function in the oral cavity, generates a similar situation as that of a beam in balance supporting a load concentrated on its free extremity. Based on this configuration, a methodology has been developed to investigate the behavior of teeth subjected to this kind of efforts, taking into consideration specific aspects of the tested teeth, such as the transversal section area and the moment of inertia. For determination of the transversal section area an image analysis program was used. For assessment of the other variables, a C++ language program was implemented utilizing the Borland Compiler C++ Builder, version 1.0, for Windows (Borland International, USA). The applicability of the developed methodology is illustrated in this article using bovine teeth. Our findings indicate that more accurate data can be obtained with the application of this methodology and that it is suitable for studies testing the flexural strength of extracted teeth, as a variable of response.

Key Words: flexural strength, flexural behavior, extracted teeth, mechanical properties.

INTRODUCTION

Extracted teeth have been widely utilized in Dentistry as test specimens for different types of investigations. According to the proceedings of the 14th and 15th annual meetings of the Brazilian Society for Dental Research (SBPqO), held in 1987 and 1988, a total of 382 and 540 studies using extracted teeth were presented, respectively (1).

Knowledge of the mechanical behavior of a tooth subjected to masticatory efforts is particularly helpful for development of research utilizing extracted teeth, i.e, studies investigating abfractions, restorative techniques and bond strength. In addition to studies that specifically evaluate mechanical properties of teeth, this can also be employed as a variable of response for assessing the effect of a number of independent variables, i.e., effectiveness of clearing techniques, effect of time, storage and x-rays, etc.

When a masticatory occlusal load is applied (considering a condition of malocclusion), teeth are subjected to high and complex forces that may be divided into axial and non-axial forces (Fig.1). The axial force, which compresses the tooth and is dissipated within the periodontium, has a global effect, both shortening and widening the tooth crown (2).

When non-axial forces (e.g. flexural forces) are acting, the teeth behave as a worn-out bar whose base approximates to the cervical region. Tooth enamel is more resistant to compressive forces than to tensile forces because human dentition is better adapted to resist to compression. Studies using finite elements have shown that dentin and enamel, together with the masticatory system, possess a design that acts dissipating the compressive forces. As a result, the tooth structure is more exposed to damage when subjected to traction forces of similar magnitude. Side forces acting upon an individual tooth will generate tension on the cervical region, on one side and on the opposite side (compressive stress) (2) (Fig. 1).

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Instead of being dissipated, tensions resulting from side forces acting on the teeth tend to concentrate near their cervical region. The magnitude of these forces on the cervical region depends not only on the magnitude and direction of the side forces but also on the distance to their application in relation to the base of the tooth, due to the fulcrum effect (2).

Several studies have conducted tests in teeth with similar geometry in order to obtain comparable results. The results are presented in units of force, without taking into consideration the influence of the distinct geometries (3-5). Teeth with similar geometry are assigned together in a same group, due to the impossibility of assembling ten or more teeth with identical geometry, which leads to distortions of the results because of the existing variations. A possible alternative would be to work with independent values of geometry by means of the analysis of the tooth area and further calculation of the stress values, considering the acting loads. Characteristics, such as area of transversal section and moment of inertia are particularly related to a given geometry and vary from one specimen to another.

On account of the aforementioned issues, we developed a method for assessing the behavior of teeth subjected to flexural efforts (non-axial component), which considers each tooth as a sample and takes into account its individual characteristics. Moreover, calculations related to the flexural behavior of the teeth involve the determination of features that are not found in the methodologies available in the reviewed literature.

This paper describes an alternative methodology for flexural strength testing that allows for investigation of certain aspects on a smaller sample size and provides more accurate results.

MATERIAL AND METHODS

To assess the behavior of teeth in response to flexural efforts, laboratory specimen testing should be carried out in a universal machine for mechanical assays, using appropriate customized devices.

Teeth can be included in plaster to simulate their fixation in the alveolar bone and the force has to be applied using an arm of few millimeters in length with a constant speed of assay until rupture of the tooth (Fig. 2). The condition illustrated in Figure 2 is similar to that of a beam in balance supporting a load concentrated in its free extremity (Fig. 3a). Considering the transversal section in *C*, at an *x* distance from A, it is possible to observe, analyzing the free body diagram *AC* (Fig. 3b), that the internal efforts in this section constitute a *P'* force of same intensity and opposite direction as that of *P* and with moment of intensity *M=P.x.* The distribution of the shearing stresses in this section depends on *P'*, whereas the distribution of normal stresses may be obtained from *M*, if the beam has been submitted to pure flexural efforts.

If σx is the normal tension at one point of the section, therefore $\sigma x = (M.c)/I$ (Eq. 1), where M = moment given by the product of the load and the distance to the setting of the bar; I = moment of inertia

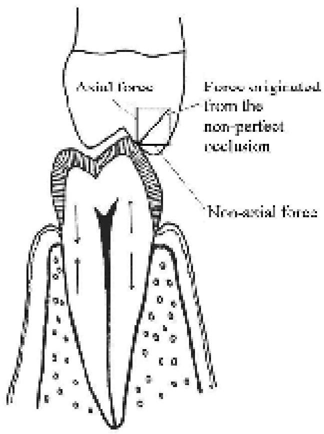

Figure 1. Forces acting during a condition of malocclusion.

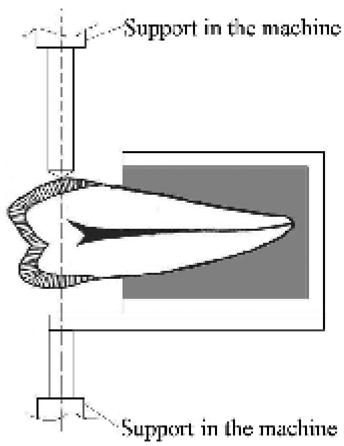

Figure 2. Schematic drawing of the customized flexural strength testing device.

of the transversal section area in relation to the neutral line; c = maximum value of the neutral surface in relation to the upper and lower faces of the bar.

The equation t = (V.Q)/(I.t) (Eq. 2) is given for calculation of the shearing tension, where V = vertical cutting force; Q = static moment; I = moment of inertia of the section in relation to neutral axis; t = width of horizontal section. This is commonly simplified by the expression (V.Q)/(I.t) ≈ P/A (Eq. 3), where P = maximum load supported by the beam; A = area of the fractured section.

A tooth submitted to flexural loads is subjected to stresses involving two components: the shearing and the normal components.

In case the analysis is performed in teeth, some initial difficulties arise, such as determination of the transversal section area of the tooth, maximum value of the neutral surface in relation to the upper or lower face of the tooth (see Eq. 1) and determination of the moment of inertia of the transversal section of the tooth, this area being irregular.

Analysis of the transversal section area

Different techniques are available for determination of the transversal section area, including comparative analysis with superpositioning to a graded transparency and use of image analysis programs, which provide more precise results, can be rapidly implemented and are thus most recommended. The image analysis programs are applied after the flexural strength test is performed and the portions of the fractured tooth are put together using a special glue (pasting), according to the following sequence: cutting of transversal sections of the teeth in the region of interest (i.e., cervical third) with a water-cooled diamond disc of a sectioning machine (e.g., Minitom; Struers, Copenhagen, Denmark); acquisition of digitized images of the cervical transversal sections, using a table scanner with 350 dpi resolution at least, in the gray scale mode and without intensity, brightness and contrast adjustments; measurement of the area with an image management software (e.g., Image-Pro Plus, Media Cybernetics, Silver Spring, MD, USA).

Moment of inertia and maximum value of the neutral surface of the tooth

The method to determine the moment of inertia of any area is described below.

Considering an area *A* situated on the *xy* plane (Fig. 4) and the element *dA* of coordinates *x* and *y*, the moment of inertia of the area *A* in relation to the *x* axis and the moment of inertia of the area *A* in relation to the *y* axis, respectively, are: $I_x = \int_A y^2 \, dA$ (Eq. 4) and $I_y = \int_A x^2 \, dA$ (Eq. 5).

The application of this methodology for teeth requires the calculation of the moment of inertia in relation to the neutral line at the moment the flexural load is applied. The moment of inertia of the areas of interest in teeth, as well as the maximum value of the neutral surface, may be obtained following the steps hereby described.

First, the centroid of the area should be determined. For such purpose, software has been implemented using a C++ language program with the aid of

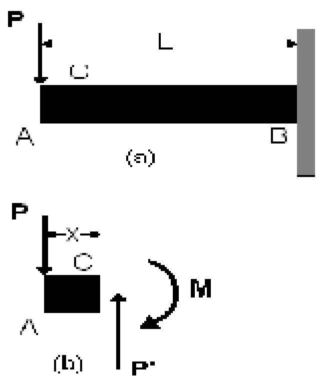

Figure 3. (a) Balance beam *AB*, (b) Diagram of free body *AC* (Beer and Johnston, 1989).

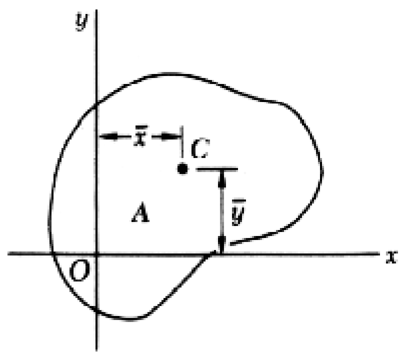

Figure 4. Schematic drawing for determination of the moment of inertia (Beer and Johnston, 1989).

the Borland C++ Builder Compiler, version 1.0, for Windows (Borland International, Scotts Valley, CA, USA). This program uses a digitalized and binary image of the area of interest and supplies an image with a definite centroid. Second, the neutral line should be determined utilizing the Paint software (Office 98 for Windows). The neutral line is extended based upon the position of fixation during the flexural strength testing. This line is perpendicular to the load application and passes through the centroid of the analyzed area (Fig. 5). Third, the moment of inertia and the maximum value of the neutral surface are calculated. To determine these parameters, it is necessary to implement a second step in the above-mentioned customized software. The input data for the software is the binary image containing the neutral line (Fig. 5).

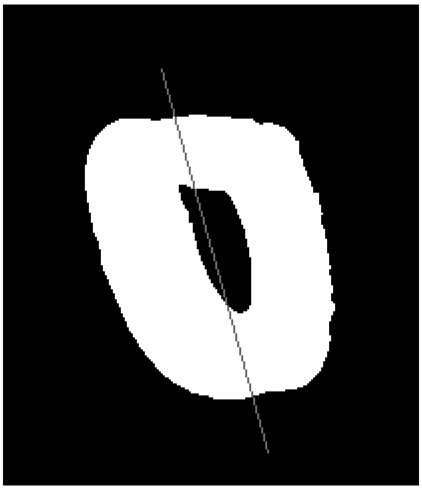

Figure 5. Neutral line setting in the binary image of the tooth.

The results obtained are given in pixel unit. Depending on the resolution used for digitalization of the images, it is possible to establish a correlation between pixels and millimeters.

To illustrate the reliability of the methodology hereby described, its application on three recently extracted bovine premolar teeth is presented. The tests were performed within 10 h after slaughtering.

Transversal sections of the teeth are shown in Figure 6. To calculate the stresses, equations 1 and 3 were utilized. The unknown values were determined according to the described methodology. Table 1 summarizes the results obtained.

RESULTS AND DISCUSSION

The results given in Table 1 (column 2) illustrate that an analysis based exclusively on the force applied does not necessarily reflect the reality. Taking into account the results for the variable “force”, tooth C would be considered the most resistant. Nevertheless, this is not necessarily true if normal stresses and shearing forces are considered. Although the teeth have similar geometry, variations in shearing force values can be of 20%. For tension values, this variation decreases to 10% (Table 1; columns 7 and 8). Theoretically, the values of force and tension should be similar

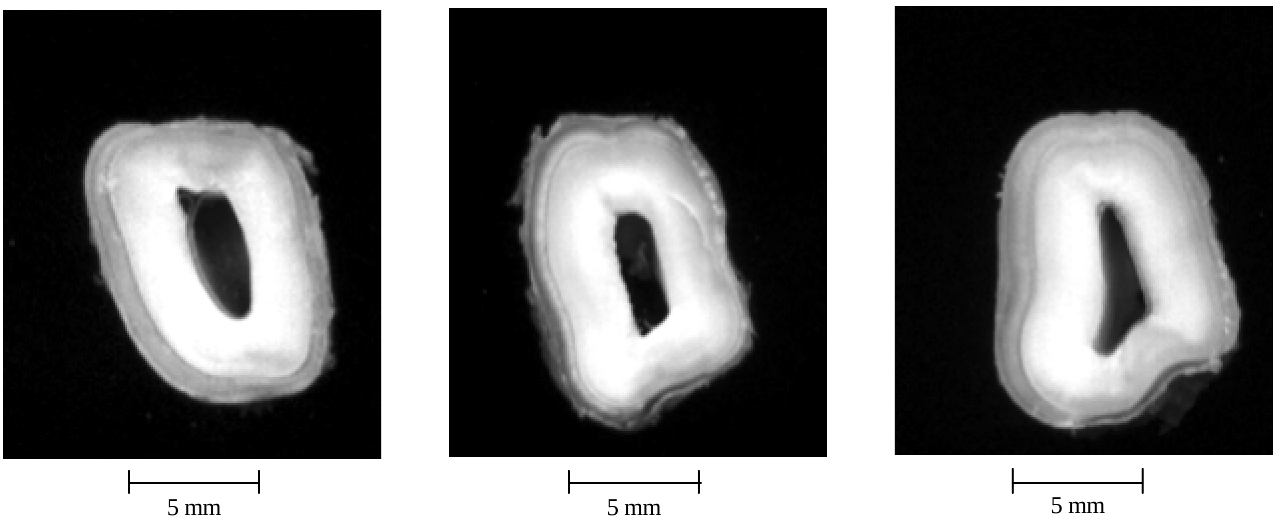

Figure 6. Different transversal sections of bovine teeth.

Table 1. Results of the application of the methodology with bovine teeth.

Tooth	Force[a] [N]	Area [mm^2]	M[b] [N.mm]	C [mm]	I [mm^4]	σx [MPa]	τ [MPa]
A	1263.3	67.0	8843.1	4.2	328.5	113.6	18.9
B	1101.9	58.8	7713.3	3.7	213.7	108.6	18.7
C	1325.2	75.6	9276.4	3.8	269.5	103.1	17.5
σ[c]	115.3	16.5	—	—	—	10.3	1.5

[a]Flexural strength results obtained in a universal machine for mechanical assays; [b]The distance between the point of force application and region of setting of the tooth was 7 mm ± 0.1; [c]Standard deviation.

for a same initial condition. These results indicate that the methodology we describe has higher accuracy than the analyses based on load values, which are currently applied in studies following this research line (3-5).

Even for an initial condition, small variations in the mechanical properties of teeth are acceptable. It should be mentioned that particularly with bovine teeth, several variations, i.e., age, breed, feeding habits and use of fluoridated water, are independent variables that are not liable to control.

The analysis of Table 1 (columns 7 and 8) also indicates coherence in the tension results. Therefore, tooth A is the most resistant, whereas tooth C is the least resistant, independently of the parameter considered (normal or shearing stresses).

The advantage of the methodology proposed in this study is that it takes into account the factor "area" and the influence of tooth geometry for determination of tension, which leads to more consistent results. It is noteworthy that, for teeth with very much different geometry, divergent load values are obtained and thus any analysis stemming from the data obtained under this condition is inadequate.

Our findings indicate that more accurate data can be obtained with the application of this methodology and that it is suitable for studies testing the flexural strength of extracted teeth, as a variable of response.

RESUMO

Tem-se observado na área odontológica a utilização de dentes naturais para a realização de pesquisas diversas (*in vivo*, *in situ* e/ou *in vitro*). O comportamento mecânico de dentes, sujeitos aos esforços mastigatórios, geralmente é utilizado como variável de resposta. Durante uma condição de maloclusão, a componente mais relevante para a integridade da estrutura dental é a não-axial (de flexão). Esta, quando atua em um dente em função na cavidade bucal, gera uma situação semelhante à de uma viga em equilíbrio suportando uma carga concentrada na extremidade livre. Com base nessa configuração, foi desenvolvida uma metodologia para o estudo do comportamento de dentes sujeitos a esforços dessa natureza. A metodologia leva em consideração aspectos particulares do dente analisado, tais como área de secção transversal, momento de inércia, etc. Na determinação da área da secção transversal, descreveu-se a utilização de um analisador de imagens. Para a determinação das demais variáveis, implementou-se um programa em linguagem de programação C++ utilizando o compilador Borland C++ Builder, versão 1.0, para ambiente Windows (Borland International, EUA). Os resultados mostraram que, com o emprego da metodologia desenvolvida, alcançam-se resultados mais precisos, sendo sua utilização adequada a pesquisas que utilizam o comportamento à flexão de dentes extraídos como variável de resposta.

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