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LITERATURE REVIEW
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Biomechanical tools to study dental implants: a literature review

Ferramentas biomecânicas aplicadas no estudo dos implantes dentários: revisão de literatura

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ABSTRACT

Since 1980, the biomechanical behavior of dental implants has received importance regarding the issue of failure in this rehabilitation system due to occlusal overload. Through bioengineering tools, several studies have been conducted to answer about the influence of different factors on the biological response. Bioengineering tools such as finite element analysis (FEA), strain gauge (SGA), photoelasticity (PEA) and digital image correlation (DIC) are widely inspiring clinical extrapolation of possible solutions in the mechanics of implantology. This study has aimed to investigate the available stress analysis methods to study dental implants' behavior through a literature review. This review started with a PubMed search from the mostly old studies of each methodology correlated to biomechanical behavior of dental implants used with dental implants studies until 2016. FEA, SGA, PEA and DIC methodologies are capable to elucidate the mechanical behavior of this rehabilitation system. However, the combination of two or more methods gives more detailed explanation and avoids limitations of a single methodology.

KEYWORDS

Finite Element Analysis; Dental Implant; Strain Gauge.

RESUMO

Desde 1980, o comportamento biomecânico dos implantes dentários tem recebido importância em relação às falhas neste sistema de reabilitação devido à sobrecarga oclusal. Através de ferramentas da bioengenharia, vários estudos têm sido realizados para elucidar a influência de diversos fatores sobre a resposta biológica. Ferramentas da bioengenharia, como a análise de elementos finitos (FEA), a extensometria (SGA), a fotoelasticidade (PEA) e a correlação de imagem digital (DIC) são amplamente utilizadas na extrapolação clínica de possíveis soluções mecânicas para implantodontia. Esta trabalho teve como objetivo investigar os métodos de análise de tensão disponíveis para o estudo do comportamento dos implantes dentários através de uma revisão da literatura. Esta revisão começou com uma pesquisa no PubMed dos estudos mais antigos de cada metodologia correlacionadas ao comportamento biomecânico de implantes dentários até 2016. As metodologias FEA, SGA, PEA e DIC são capazes de elucidar o comportamento mecânico deste sistema de reabilitação. No entanto, a combinação de dois ou mais métodos fornece explicações mais detalhadas e evita limitações de uma única metodologia.

PALAVRAS-CHAVE

Análise de Elementos Finitos; Implante dentário; Extensometria.

INTRODUCTION

From the fundamental studies of Branemark [1] with the creation of a secure protocol of fundamental concepts, the implant was consecrated in modern dentistry as a tool for oral rehabilitation with reliable results. To achieve today's standards, implants have undergone several changes with the focus on treatment survival. Biomechanical behavior began to receive importance regarding the issue of failure of the implants due to occlusal overload and has been defined as one of the main causes of failure in this rehabilitation system [2].

With normal mechanical stimulus between 50 and 150 $\mu\varepsilon$, it is possible to maintain the bone condition; when stimulus is less than 50 $\mu\varepsilon$, the bone tends to reabsorb due to disuse. Values above 1500 $\mu\varepsilon$, tend to activate the lamellar bone remodeling, resulting in reshaping and strengthening. Values above 3000 $\mu\varepsilon$ promote disorganization remodeling which causes irreversible microdamage to the structure [3].

With possible mechanical problems in a geometric system and its transmission capacity of strains to bone tissue, in vitro studies are achieving more visibility in order to study the biomechanical behavior of implants and rehabilitation treatment. Through bioengineering tools, several studies appear to give insight into the influence of different factors on biological response [4,5]

Bioengineering tools such as finite element analysis, strain gauge and photoelasticity are widely inspiring clinical extrapolation of possible solutions in the mechanics of implantology [6], in addition to digital image correlation [7]. Thus, this study aimed to investigate the available stress analysis methods to study dental implants' behavior through a literature review.

MATERIAL AND METHODS

This review started with a PubMed search from mostly older studies of each methodology used with dental implant studies until 2016. The search was conducted using the following key words: Finite Element Analysis and Dental Implant, FEA and Dental Implants, Strain Gauge Analysis and Dental Implant, Photoelasticity and Dental Implants, Photoelasticity Methodology, Photoelastic and Dental Implants, Digital Image Correlation and Dental Implants. If it was not possible to obtain the full text, the electronically available abstracts were collected. Thus, the inclusion criteria for articles were as follows: (1) Articles related to biomechanical behavior of dental implants, and (2) abstracts were obtained when the full texts could not be obtained. Articles about implants for orthopedic usage were excluded from the review.

Strain Gauge Analysis (SGA)

For implantology, linear extensometer began as a tool for in vivo studies, first used in dogs treated with dental implants [8]. Five years later, it was applied in implanted human patients to verify the improvement of muscle power and to analyze the increase of masticatory stress [9,10].

SGA consists of a resistor with a conductive wire deposited on a small insulation area. This area has to be glued onto the structure to be tested and the dimensions of structure variations are then mechanically transmitted [9,10].

Another *in vivo* applicability of Strain Gauge occurred due to the possibility of rehabilitating a single patient through different treatments and then comparing the dissipation of stress on the fasteners, allowing to better understand differences between fixed implant prostheses and supported implants [11].

SGA started to be used in laboratory studies involving implants only after proving in vivo efficiency, comparing different restorative materials and their influence on bone behavior [12]. This capable numerical measurement allowed for statistical analysis of the findings. However, the correlation with qualitative tools such as photoelasticity made the biomechanical behavior more elucidated and didactical during discussions [13].

This numerical method is sensitive to small restorative material variations and also to the environment used. The comparison of the same situation in vivo and in vitro can show completely different results [14]. Thus, in vitro analysis achieved credibility by controlling the influence of variables in the results. Other methodologies such as photoelasticity complement the results from SGA ensuring that the gauges are truly measuring high voltages at high stress regions [15]. Several suggestions have been published through the necessity of standardized studies conducted in laboratories and to enable comparison of the results with other studies. For example, the use of a human' jaw from a fresh cadaver [16] or a developed resinous material which has similar elastic modulus to the bone tissue [17]. Validation of this material occurred approximately 10 years after a few studies had been published with polyurethane [18].

Finite Element Analysis (FEA)

FEA models are created in computers to calculate strain, microstrain and displacement. This methodology has the advantage of allowing simulation of various conditions to be easily modified, allowing the measurement of stress distribution around implants in areas of difficult clinical access.

In order to understand the stress generated in the masticatory system, FEA was first used as a tool of dental studies in 1973 with a two-dimensional (2-D) model [19]. With the processing power development of computers, more complex studies have been carried out [20, 21]. In addition, three-dimensional (3-D) modeling is now applied in the field of implant dentistry concentrating on distribution of stress in bone tissue due to different elastic modulus and fixations.

As the possibility of success for analyzing the same objective with 2-D (faster and simple) and also with 3-D analysis (more complex), the choice of which method to use became apparent [22]. And, comparing both models, 3-D model offers more realistic results.

The development of tools able to model and calculate increasingly complex geometries was possible as computers became more efficient. In implantology, the most complex treatments began to gain a mathematical view (with FEA) of the generated bone tensions generated, such as angled abutments, overdentures with clip bar [23], and cantilever [24].

Detailed factors such as the presence or absence of threads on the implant surface, or the separation of cortical and medullary bone with different properties became part of the design methodology [25]. Results from the concentration region and stress distribution became increasingly compatible with biological explanations for observed remodeling.

Technique sensitivity for any dimensional variation showed different results. For example, in comparing titanium implant wall thicknesses it can be observed that thicker walls generate lower stress values [26].

This sensitivity to any variation present in the 3D model has put the validity of the results in vogue. In previous study, different models of human jaws were made and different stress results were obtained. However, the authors couldn't be sure which one represented reality [27].

FEA and SGA are very helpful to validate a mathematical model due to correlation by two numerical methods. In implants with conical connection for example, the authors concluded that the two methods were similar, however, there were differences between the quantifying methods [28].

Nevertheless, FEA is well defined and methodically explained [29]. FEA makes in silico studies possible due to the control of influential variations on the results and the excellence of the software involved in obtaining 3-D models; this included the development of scanners capable to create a geometry as close as possible to reality. Finally, the Digital Image Correlation method has validated the FEA since it had never been assessed in the dental field [30].

Photoelasticity Analysis (PEA)

PEA provides good qualitative information on the concentration of stress; however, it produces limited numerical information. PEA is an important tool to determine the critical stress points in the material and is commonly used for determining stress concentration factors in irregular geometries [31].

The early use of photoelasticity as an alternative to assess the concentration of stress on osseointegrated oral implant models occurred in 1980, with variation in the type of anchor and application loads in the best design and installation for fixed bridges on implants [32]. However, since then it was a methodology used in the study of dental structures [33].

Then, PEA started to be used as a complementary approach for developing materials for implants, materials for components [35,36], and implant designs [34]. PEA is also used on investigations of components angulation [13,15,37], type of fixed prosthesis [38,39,40,41], different systems of implants [36,37,39,42,43], load variation [42,44,45], length of implants [43,44], diameter implants [44], implant angulation [45,46], maladjustment [47], type of attachment [48,49], insertion depth [37], type of retention [50], and type of internal connection [51]. The tension regarding the evaluation generated in cemented or screwed fixed prostheses is also a very useful subject matter through PEA [42,52].

The PEA model is the object of study. The photoelastic fringes developed in the model are photographically recorded. The number of fringes indicates the voltage, and the stress concentration occurs due to the proximity of the fringes [35]. In general, PEA demonstrates the quality, amount and distribution of power on an object by pattern fringes that appear as a series of different and successive contiguous (isochromatic) color bands. Each band represents a different degree of birefringence relevant to the underlying stress in the tested part. The outline of the isochromatic fringe is determined by stress in each area and is equal principal stress differences. Thus, the color of each band uniquely identifies the birefringence or order of fringe (and stress level) everywhere along this band [35].

The major advantages of the PEA is the ability to view stresses in complex structures (such as oral structures) and observe patterns of tension in the complete model, allowing the researcher to locate and quantify the magnitude of the stress [6]. However, the PEA technique does not have the numerical resolution to discern stress gradients in the area of microstrains. Therefore, the influence of microstrains could not be examined in detail [35]. From the timeline (Figure 1), it is possible to observe a chronological sequence of the emergence of these methodologies and the initial use time as complementary methodologies.

Digital Image Correlation (DIC)

Digital Image Correlation (DIC) has emerged as an alternative to measure the distribution of surface tension on materials [53,54,55] throughout the specimen, unlike the strain gauge [55]. Through a camera attached to a charging device, multiple images of the specimens are captured and analyzed using software [53,55] that shows the distribution of stresses on the surface in detail.

In dentistry, DIC is used to study different types of prostheses [55,56] and retention [57], prosthesis materials [7], bone strain induced by implants [30], and displacement of implant abutments [58].

It should be noted that the displacement of the color gradient as the stress distribution are not sufficient for determining a complete interpretation of a particular object of study [59,60]. However, we can evaluate the stress

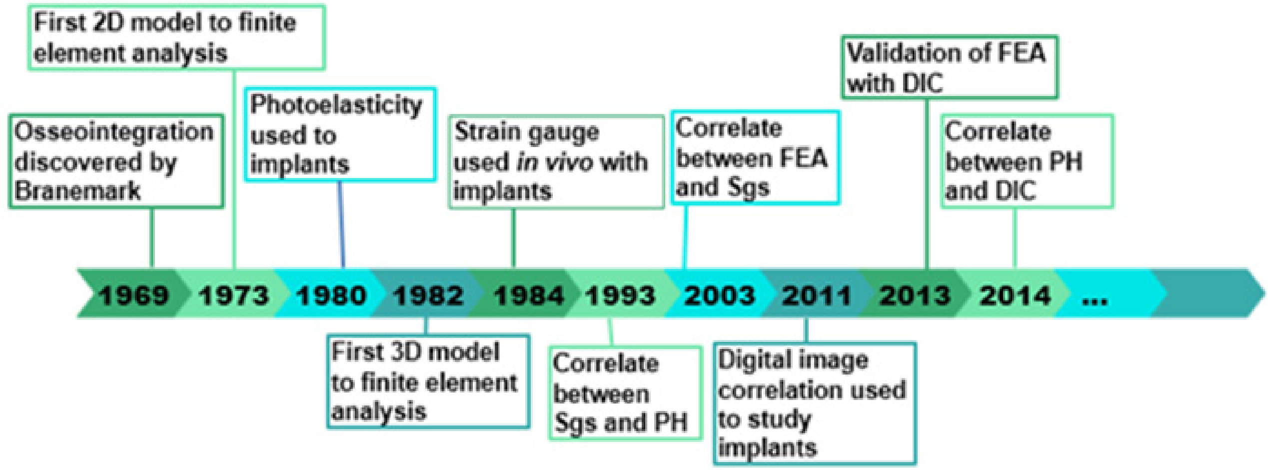

Figure 1 - Chronological sequence of the emergence of SGA, FEA, PEA and DIC methodologies and the initial use time as complementary methodologies for studying dental implants.

distribution over the entire surface, unlike the SGA covering a small area.

DISCUSSION

SGA has a limitation of not exactly identifying the load that is transmitted through the implant to the bone, as the devices cannot be fixed on the implant's surface [9,10], which may result in lower values.

In comparing FEA and SGA on implants with conical connection, the mathematical analysis was subsequently performed by the experimental model. The authors concluded that both methods were similar, however, there were differences between the quantifying methods. Similar results between PEA and FEA are capable [51] but in the qualitative sphere. Considering PEA and SGA, the authors did not present a consensus [4,13,15].

Recently, FEA methodology has been validated by DIC, since it had been borrowed from engineering and never before actually evaluated [30].

In comparing PEA and DIC methods [60] in the analysis of stress / strain transferred by implant prostheses to peri-implant tissues, the authors found that both methods showed similar results, being able to indicate where the complications associated with stress / strain can arise. However, DIC was shown to be apparently less sensitive than other methods of measuring tensions and is not only restricted to polarized translucent materials [60]. DIC is also less sensitive to environmental vibrations than SGA. Also, DIC can detect the movement of a rigid body and simultaneously measure shifts in 3 dimensions (mm to μm) [59,60].

CONCLUSION

To analyze stress in dental implants, SGA, FEA, PEA and DIC methodologies are capable to elucidate the mechanical behavior of this rehabilitation system. However, the combination of two or more methods gives a more detailed explanation and avoids limitations of a single methodology.

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