

JPL Quarterly Technical Review

Volume 2, Number 4

January 1973

Index: bioengineering

Unified Approach to the Biomechanics of Dental Implantology

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The human need for safe and effective dental implants is well-recognized. Although many implant designs have been tested and are in use today, a large number have resulted in clinical failure. These failures appear to be due to biomechanical effects, as well as biocompatibility and surgical factors.

This article proposes a unified approach, using multidisciplinary systems technology, for the study of the biomechanical interactions between dental implants and host tissues. The approach progresses from biomechanical modeling and analysis, supported by experimental investigations, through implant design development, clinical verification, and education of the dental practitioner.

The result of the biomechanical modeling, analysis, and experimental phases would be the development of scientific design criteria for implants. Implant designs meeting these criteria would be generated, fabricated, and tested in animals. After design acceptance, these implants would be tested in humans, using efficient and safe surgical and restorative procedures. Finally, educational media and instructional courses would be developed for training dental practitioners in the use of the resulting implants.

Introduction

The development and application of safe and effective dental implants as replacements for natural teeth has long been the main goal of implant dentistry. The clinical significance for such development and application is obvious. In the United States alone, there are approximately 56,000,000 teeth extracted annually, and there are over 850,000,000 missing teeth in our population (Ref. 1). People who are partially or fully edentulous would be materially aided through the use of functional, long-lasting implants that prevented resorption of the alveolar bone while preserving normal oral function.

Yet, as great as the need appears to be, safe and effective human implants are still not available. Many designs and devices have been attempted, but most have resulted in clinical failure. These failures appear to be due as much to the lack of consideration of biomechanical factors as to anatomical, biological, and surgical requirements. Implant designs have been developed on a trial-and-error basis largely without consideration of the design requirements for proper mechanical stimulation of the alveolar bone of the mandible or maxilla.

Dental biomechanical research efforts are under way to place the development and application of dental implants on a sound rational basis to ensure long-term clinical success. Important contributions have recently been made in many areas, including biomechanical modeling and analysis (Ref. 2), studies of tissue compatibility with implant biomaterials (Ref. 3), studies of biophysical properties of hard tissues (Ref. 4), and characterization of cellular response to mechanical loading (Ref. 5). However, these contributions primarily reflect the results of individual or group researchers working on specialized aspects of the dental implant problem. What is needed is a unified approach to the biomechanics of dental implants that integrates the results of these researchers and uses multidisciplinary systems technology to develop implant designs with a high probability of clinical success. Such an approach, supported by feasibility demonstration data, is described in this article.

Description of Approach

The unified approach to the biomechanics of dental implantology consists of five phases. The relationship of these phases is demonstrated in Fig. 1.

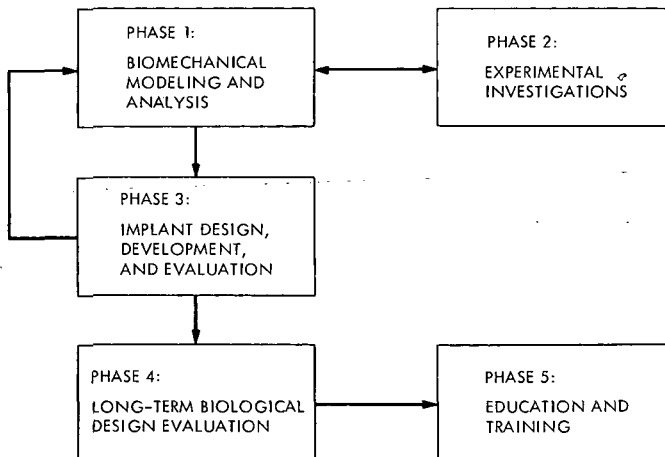


Fig. 1.—Unified approach to the biomechanics of dental implantology

Phase 1: Biomechanical Modeling and Analysis

The first phase of the approach involves the development of three-dimensional, finite-element mathematical models of the human mandible and maxilla and the analysis of these models using computerized techniques. The models require the incorporation of biological parameters such as bone bioelectricity, as well as physiological, anatomical, and mechanical features, in order to develop biomechanical relevance and clinical significance. Many of these parameters have already been defined in various research efforts reported in the literature.

The types of biomechanical models to be developed include models of the mandible and maxilla, both with and without implants. Analysis of the normal models under occlusal loading would yield baseline data on the natural biomechanical response of the mandible and maxilla. Analysis of the models containing implants would enable comparison with the normal baseline response to assess analytically the implant design function and develop biomechanical design criteria for implants.

Analysis requirements include the use of computer techniques capable of handling time variation in material properties and loading, since these are natural oral conditions. In addition, it appears necessary to develop what might be termed a biomechanical bone remodeling algorithm to predict analytically the long-term success potential associated with a given implant design. Such an algorithm has already been proposed (Ref. 6). This algorithm essentially accounts for the time variation in mandible or maxilla geometry due to bone resorption and formation in the local region of the implant. This anatomical change is caused by the applied load on the implant and is manifested by the resulting physiological alterations in the supporting bone structure (Ref. 4).

Phase 2: Experimental Investigations

In order to develop credibility in the analytical predictions, it is necessary to perform experimental investigations to verify the biomechanical models and/or determine areas of possible improvement. These investigations should be done *in vitro* and *in vivo*, preferably using non-destructive, non-contacting test techniques. Techniques of this type are needed to measure true test medium response without disturbance due to mechanical attachments or probes.

Fortunately, several test techniques satisfying these requirements are available, such as holography, electrical impedance measurement, acoustics, and radiography. (The first two techniques have been investigated for this application by the authors and will be discussed later.) Suffice it to say, however, that more work in this area is needed to gain a better understanding of mandibular and maxillary biomechanical response.

During this phase, consideration should also be given to developing short-term biological techniques that could accurately predict long-term bone response to mechanical loading of implants. These techniques, which would

be based upon cellular activity observations and verified through animal testing, would identify sets of morphological and biochemical parameters associated with the initiation of bone resorption. Application of these techniques would provide a powerful means of immediately assessing the clinical success potential of dental implants.

Phase 3: Implant Design, Development, and Evaluation

This phase of the approach utilizes the results of the previous phases and incorporates further the dental and biological considerations necessary to develop sound implant devices for human usage. Recognizing that the resulting implant designs must ultimately be converted to dental implants available to the practitioner and patient, consideration must be given to the manufacturing, processing, and cost of dental implants. Thus, this phase of activity consists of the development of implant design criteria and implant designs, the biomechanical evaluation of each design using the biomechanical bone remodeling algorithm, the fabrication and laboratory evaluation of specific implant designs, and the subsequent evaluation of these designs in short-term animal testing. The design criteria to be developed include:

- (1) Biomechanical criteria, which would consist of implant configuration and physical-property requirements based upon the results and experience gained in the previous phases.
- (2) Biological criteria, which would include requirements relating to tissue compatibility, systemic toxicity, and carcinogenesis.
- (3) Dental criteria, which would reflect consideration of surgical and restorative procedures, bacterial invasion, epithelial attachment, and implant function.
- (4) Anatomical criteria, which would include design constraints based upon implant site anatomy and intended implant usage.
- (5) Production criteria, which would be based upon cost and quality-control requirements.

Implant designs would then be developed that satisfy these criteria. The design phase would include the development of new designs, as well as consideration of existing implant devices. Designs developed in this manner would automatically relate acceptable implant shape with suitable biomaterials and account for design flexibility to satisfy clinical constraints.

The implant designs would be analytically evaluated through the use of the bone remodeling algorithm. The algorithm would estimate the probable time-sequence stages of resorption and formation of alveolar bone, which take place in the mandible or maxilla in response to the presence of a design implant under specific loading conditions. Each implant design would be studied in each of the proposed modes of application under a range of loading conditions. Using this technique, it would be possible to obtain rapidly a quantitative estimate of the long-term success potential or reliability of each implant design.

Those designs that meet the design criteria will be fabricated for laboratory analysis and short-term testing *in vivo*. The fabrication considerations for the designs consist of the feasibility of mass production and the cost per unit. The main thrust would be to generate implant designs that can be produced at low cost and in large quantities, if needed, from readily available materials.

A series of laboratory tests would be performed on each implant design to determine its reliability under a given function and its probable mechanical lifetime. The types of tests would include strength and physical property characterization, corrosion resistance, and thermal and fatigue behavior.

The most promising implant designs, as determined by algorithm evaluation and laboratory screening, would be fabricated for short-term *in vivo* animal testing. These tests would be designed to demonstrate short-term implant performance and to supply information whereby probable long-term function could be estimated. Included in these tests would be the application of the previously discussed short-term biological techniques to predict long-term biomechanical response of the mandible or maxilla containing dental implants.

Those designs that, both analytically and biologically, appear to maintain the supporting alveolar bone (or at least not mechanically irritate it) and appear to allow rapid healing of the surgical site and demonstrate good clinical signs (e.g., gingival condition, sulcus depth, and plaque collection) would be tested on a long-term basis in animals and humans. Those designs that appear to stimulate rapid alveolar bone resorption would be returned to the design stage for modification of those portions of the implant configuration affecting tissue response.

Phase 4: Long-Term Biological Design Evaluation

For the animal tests, implants would be placed in both fresh extraction sites and healed edentulous sites according to their projected use. Splinting or self-immobilization techniques would be developed for each implant design as needed. The implants would be restored after a suitable healing period. The long-term effects of normal occlusion, hyperocclusion, and implants placed at an angle to occlusal loading would be studied.

Long-term clinical trials would then be conducted in humans on those designs that functioned well during the first years of long-term animal testing. A human case-study population would be developed so that biostatistically significant data could be obtained from reasonably small numbers of patients in each implant test category. Patient selection criteria would be established for the study of each implant design. These criteria would be formulated both for control of the experiment and for testing their application by the dentist in practice.

A standardized-treatment planning format would be designed for each implant configuration. When a patient is accepted, a treatment schedule would be documented. Comparison could then be made, after the treatment

of many patients, to determine how well such treatment plans can be maintained and to identify what difficulties arose and how they were resolved during each case study.

A variety of surgical procedures would be employed based upon the proposed function of the implant. In each edentulous site, the alveolar bone would be exposed to allow good visual inspection of the site for final location of the implant position, final planning of the surgical procedure, and final choice of implant size. Use of full thickness flaps or removal of a tissue plug would be dependent upon implant design.

Techniques of socket preparation would also be studied so that step-by-step procedures could be developed for each design. Socket preparation procedures would be designed to avoid penetration of the mandibular canal or maxillary sinus or perforation of the buccal or lingual plates. These procedures would be simplified so as to be within the capabilities of the general dental practitioner.

A primary focus of the human implant case studies would be to develop step-by-step procedures and guidelines for restorative procedures. Indeed, the total treatment plan; the choice of implant location, design, and size; and the surgical procedure to be used should all be determined in part by the intended function of the final restoration. Naturally, maintenance of good gingival tissue health and crestal alveolar bone will depend on the contouring of the crown and on the geometry of the restoration-implant and implant-tissue interfaces. Thus, the development of simple restorative procedures that can be taught to the average general practitioner in a logical, step-by-step manner would be of critical importance.

The human studies would also consider the forms of postoperative care required for each implant and would provide recommended steps for such care during healing and following restoration. Emergency procedures would be documented for implant removal and for site treatment following removal.

Finally, patient oral-hygiene requirements would have to be developed for proper maintenance of each implant type. This is necessary to ensure prevention of implant failure due to hygienic causes.

Phase 5: Education and Training

After standardizing the procedures to be used in applying the dental implants, a series of educational media would be prepared for use in training dental practitioners. These media would take the form of training manuals, films, video tapes, slide-tape presentations, and documentation of human case studies and animal research results. These media would present in detail all factors to be considered in the selection of patients and appropriate implants, treatment planning, surgical and restorative procedures, patient oral hygiene, and patient education.

Feasibility Demonstration

The feasibility of implementing the above approach was largely demonstrated through a pilot program (Ref. 7) and a large-scale private research project investigating the application of vitreous carbon as a dental implant biomaterial.

Mathematical Modeling and Structural Analysis of a Dried Human Mandible

In the pilot study, an integrated biomechanical modeling, analysis, and experimental program was conducted using a dried human mandible. Such a specimen was chosen because it simplified the initial exercise of each phase of the program. Although the dried mandible did not represent the *in vivo* system, this exercise did verify modeling capabilities and the experimental procedures to be used in the above approach. A finite-element, half-symmetric, structural model of the mandible was developed (Ref. 2). The model, based on a first-order approximation of the stiffness and geometry of the human mandible, is shown in Fig. 2. The model geometry was derived from measurements taken of the actual mandible specimen using horizontal sectioning techniques, and the material properties were derived from the literature.

Loading on the occlusal surface of the first bicuspid was used to study the analytical response of the mathematical model. This tooth was selected

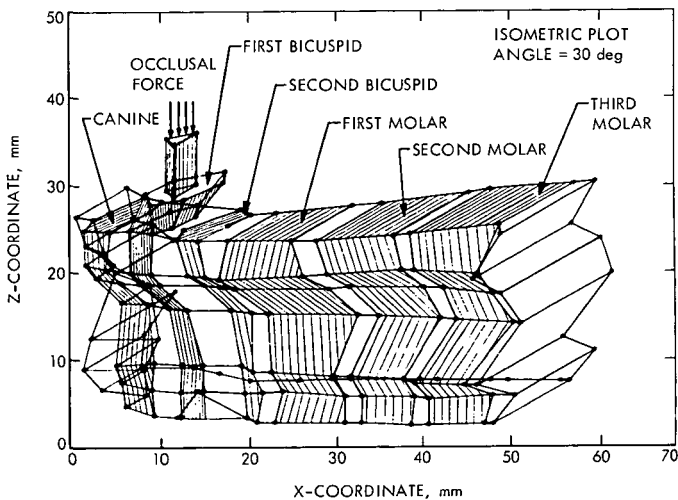


Fig. 2. Three-dimensional view of half-symmetry mathematical model of mandible

because of its clinical significance and ease of modeling. Nodal stresses and the deformation of the model under the applied load were generated using the general-purpose computer program ELAS (Ref. 8). As a check on model accuracy, predicted deformations were compared with test results obtained using holographic interferometry applied to a human mandible in the dried state. The holographic technique was chosen because it offered the advantage of non-contact mapping of the extremely small displacements occurring in the deformation field of a mandible specimen.

A qualitative comparison of analysis and test displacement contours (Fig. 3) indicates that good agreement between test and theory was achieved. The direction of the numerical contour slopes predicted analytically is consistent with that of the fringe slopes obtained holographically. In general, slopes are negative in the mesial direction and positive in the distal direction relative to the loaded first mandibular bicuspid.

Specific investigation of the holographic data also shows a condition of looping fringes between teeth in the local area of loading. Stiffness variation between regions of high (dentin) and low (alveolar bone) elastic modulus is apparently the cause. This effect appears to have been predicted analytically, as is evidenced in the low left-hand region of the numerical contours.

Clearly, model extension and improvement to represent the clinical human condition will require the incorporation of biological parameters, as discussed above. Experimental verification of improved biomechanical models using non-contacting techniques such as holography will also be required.

Detection of Bioelectric Responses in a Dried Human Mandible

Fig. 4 shows the apparatus used to detect bioelectric responses in the dried human mandible under loading conditions similar to those used in the

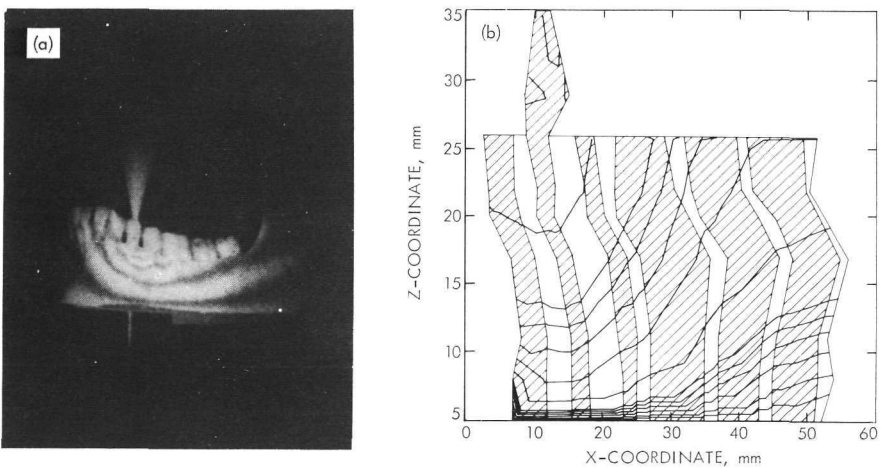


Fig. 3. Comparison of displacement contours: (a) hologram and (b) computer predictions

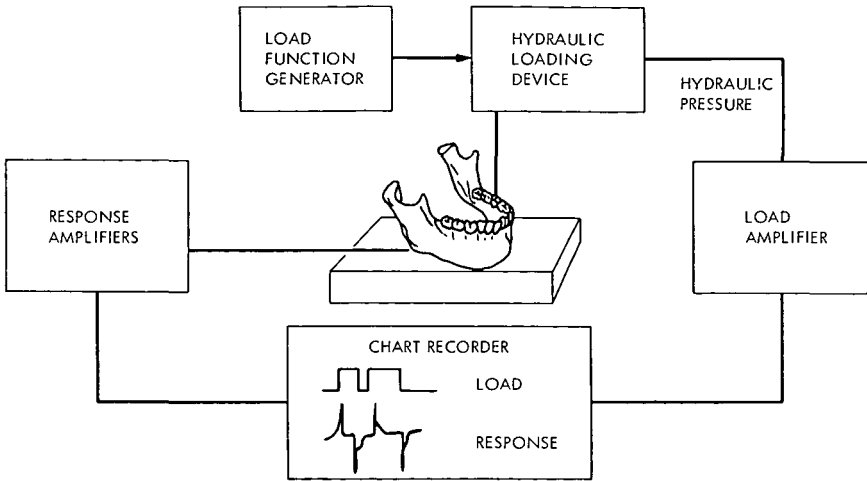


Fig. 4. Bioelectric response experimental apparatus

model and holographic studies. This experiment was undertaken as a prelude to determining the bioelectric material properties of the *in vivo* mandible and maxilla. These properties are necessary to biologically characterize improved biomechanical models in order to relate mechanically induced deformation to bone remodeling response (Refs. 4 and 5).

A static load was applied to the first bicuspid of a dried human mandible that was supported on a block of epoxy resin and loaded through an epoxy rod. The epoxy block and rod served to insulate electrically the mandible from the loading apparatus in order to prevent grounding of the bioelectric signals. Bioelectric surface signals resulting from mandible loading were amplified and recorded on a strip chart recorder.

The experimental apparatus worked satisfactorily, and analysis of the data obtained is in progress. The results achieved thus far, coupled with the results reported by others (Refs. 9 and 10) in determining the bioelectric response of bone, strongly attest to the feasibility of characterizing the *in vivo* bioelectric response of the human mandible. It is clear, however, that a technique to map rapidly the bioelectric surface response of hard tissues would facilitate experimental procedure and improve data accuracy.

Investigation of Cellular Activities Involved in Bone Resorption

Studies have been conducted on the changes in cellular activities and metabolism of hard tissues after stimulation of bone resorption by hormonal and drug stimuli. During these studies, a number of testing procedures, including tissue biopsy techniques, were developed and evaluated. (Details of some results of these studies are presented in Ref. 11.) At a minimum, these studies have served to establish the feasibility of using cellular activity parameters as short-term markers for bone resorption.

Design and Development of an Endosteal Implant

A large-scale research program has been undertaken to develop and test an endosteal implant made from vitreous carbon. Short-term animal histological studies designed to evaluate material biocompatibility and epithelial attachment to the implant have been completed. Long-term work is in progress to evaluate systemic toxicological and carcinogenic effects due to the implant biomaterial.

In the course of these studies, surgical and restorative procedures associated with the implant designs, which were initially empirically evolved, have been developed. These procedures were designed to allow the implants to function both in free-standing situations and as abutments for fixed prostheses.

A series of educational aids has been developed for use in training dental practitioners in the proper procedural use of the carbon endosteal implant. These aids include a film, training manual, and laboratory exercise, as well as formal continuing-education courses.

The experience obtained in this program has demonstrated the need for implant design development using an integrated scientific and clinical approach such as described above.

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