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BIOMECHANICAL INVESTIGATION OF IMPLANT FAILURE IN BONE-BIOCERAMICS JUNCTURE SYSTEM

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Mechanical supportive organs such as bone and teeth have a juncture system according to their functions. Conventionally, bioceramics or biometals and bone tissue are bonded directly in clinical use as osseointegration or ankylosis. However, direct bonding of bioceramics to living osseous tissue can not stand up in the bonding site under severe repeated loading because of differences in elastic moduli from each other. In mammals, four major juncture systems are known among different skeletons. They are constructed with different elastic moduli or have different mobility between each other so they have to have a jointing system instead of ankylosis or osseointegration. Bioceramic skeletons and bone tissue with a direct bonding system can be formed easily without loading, and stand up for a long term if very weak loading is applied. Thus, without severe repeated loading, osseointegration or ankylosis can be attained easily between different substances with different material constants. Then why is osseointegration or ankylosis disrupted or destroyed under severe repeated loading? To solve this problem, numerical experiments by means of finite element analysis (FEA) were carried out using artificial root models implanted in the mandible in a plane strain state.

1. INTRODUCTION

Artificial roots of gomphotic and ankylotic conditions were analyzed under $6kgf/mm^2$ loading with inclinations of 90° and 45° to the horizontal plane. The model, material constants, and experimental conditions have already been reported[1]. The artificial roots used were of two different types, i.e., corrugated cone and cylindrical. The results were compared to specimens obtained from animal experiments. The results of FEA showed that the periimplantium played a very important role in converting the principal

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stress into parallel and normal trajectories. The Mises equivalent stress distribution patterns were also influenced by the periimplantium to mitigate and equalize stress. In ankylosis, stress is distributed in cortical bone in a concentrated manner. The principal stress trajectories run continuously from the artificial root to the ankylotic peripheral bone tissue. Severe bone destruction was observed in cortical bone around a similar type dental implant in an animal experiment several years postop[2]. The destruction observed coincided with the stress-concentrating site of the analyzed model. Elastic moduli refer to the rate of shrinkage under loading. Therefore, different materials of a stiff bonding system i.e., ankylosis or osseointegration with different elastic moduli, disrupted under severe loading because of continuing principal stress trajectories between each other.

Regarding the junction of bioceramics with original bone, which have quite different material constants of Young's modulus and Poisson's ratio from each other, synostosis (ankylosis) cannot stand up under severe loading conditions. Therefore, it is necessary to introduce either a new junction system for the interface between the biomaterial mechanical organ and original bone, or a stress breaking system or principal stress trajectory conversion system in ankylotic artificial root[3].

This time, we observed implant failures concerning artificial roots in functioning jawbone using adult dogs and Japanese monkeys. Conventionally, most experiments of dental implants using animals have no adequate masticatory loading. Therefore, the important problem of implant failure and bone destruction could not be resolved. We also carried out finite element analyses (FEA) concerning the root function.

For investigation of the histological difference between gomphotic and ankylotic teeth, animal experiments of functional and nonfunctional groups were carried out. For investigation of the biomechanical difference, stress analyses with model conditions approximating the animal experiments were also carried out. Thereafter, the results were compared. Fibrous tissue around roots with alveolar bone proper was observed in specimens of the functional group[4-8]. Ankylosis of the artificial roots to the surrounding bone was observed in specimens without occlusal function. Severe bone destruction was observed in cortical bone around ankylotic dental implants in the animal experiment. The pattern of bone destruction under the usual occlusal function in the experiment and the finite element analysis (FEA) pattern showed a close correlation. The fibrous juncture system around the bioceramic has the most important role, after which the stress mitigates and disperses, and the principal stress trajectories are converted to two components of parallel and orthogonal orientations. It was proved that effective conversion of the principal stress trajectories depended upon the undulated morphology of the bioceramic artificial root. From these experiments, schemata of bone remodeling around gomphotic artificial root and of bone destruction are shown. Considering these results, a new type of ankylotic artificial root with a shock-absorbing system was developed.

2. METHODS AND MATERIALS

2.1. Animal experiments

Artificial roots of the fibrous tissue attachment type made of dense apatite, titanium, and ZrO_2, 4mm in diameter, were implanted in adult dogs. For the nonfunctional group, we implanted the roots deeply at the level of the gingiva. Then the dogs were fed a soft diet. For the functional group, the artificial roots were implanted with the occlusal part extruded to the oral cavity through the gingiva. Then the dogs were fed a solid diet so as to apply physiological movement to the roots by mastication. After fixed periods (3w 6w, 8w, 12w, and 72 weeks) undecalcified and decalcified specimens for light microscopy were prepared. Specimens were stained with H-E, Masson-trichrome, and toluidine blue, then were studied histopathologically. For the monkey group, masticatory loading was applied after implantation for a long term, after which masticatory loading was excluded. Hydroxyapatite artificial roots were implanted in the mandible and maxilla of Japanese monkeys. Two years after implantation, the artificial roots were covered with crown splint to remove masticatory and occlusal loading. An additional two years later, the artificial roots were recovered to make specimens. For an ankylotic artificial root system, macerated bone specimens of osseointegration systems implanted in the mandible were made after long-term function.

2.2. Finite element analyses relating to gomphotic and ankylotic apatite artificial root -Comparison of stress distribution patterns around gomphotic and ankylotic roots

The stress distribution of the gomphotic and ankylotic systems around newly tailored artificial roots of standard type, 5mm in diameter were analyzed in implantation models by FEM. The models of the mandibular molar region with artificial roots implanted were made in the plane stress state. Element divisions of a gomphotic (Figure 1) and ankylotic standard type artificial root were set. Static load of 6kgf/mm was applied to the artificial roots with 90° and 45° inclinations to the horizontal plane.

3. RESULTS

3.1. Animal experiments

3.1.1. Nonfunctional group

Observation of an undecalcified specimen 3 weeks to 12 weeks after implantation revealed that the artificial roots were ankylotic, namely in direct contact with surrounding bone tissue, which has no tooth supportive structure, i.e. periodontal ligament and alveolar bone proper with trabeculae (Figure 2). Using Japanese monkeys, after two years of artificial root implantation, fixation with crown splint to exclude masticatory functional loading to the artificial root was carried out. After that, two years later, the specimens were recovered and microscopic observation was carried out. Ankylotic artificial roots were observed. Artificial root and jawbone ankylosis took place only at the cortical site and almost no bone formation around the root could be seen (Figure 4). Bone structure around the artificial root was quite different from that of the control of a normal dental tooth (Figure 3)

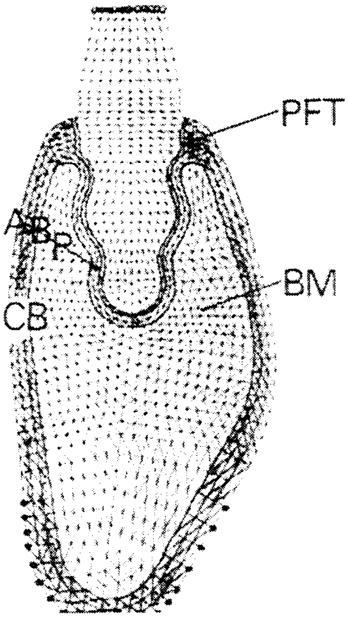


FIGURE 1 FIGURE 2

FIGURE 1: FEA model in plane strain state and element division of gomphotic artificial root.

FIGURE 2: Ankylotic hydroxyapatite artificial root. 3 weeks postop. Ankylosis could be obtained easily without loading.

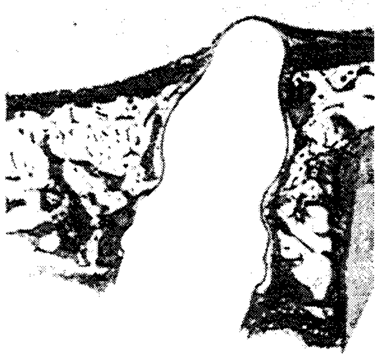
FIGURE 3 FIGURE 4

FIGURE 3: Natural gomphotic tooth root and maxilla of monkey, for control of artificial root of Figure 4.

Figure 4: Ankylotic hydroxyapatite artificial root 4 years postop.

3.1.2. Functional group

Observation of an undecalcified specimen 8 weeks and 6 months after implantation revealed that the artificial roots were in direct contact with fibrous tissue, and bone formation had occurred resembling alveolar bone proper with trabeculae (Figures 5-6).



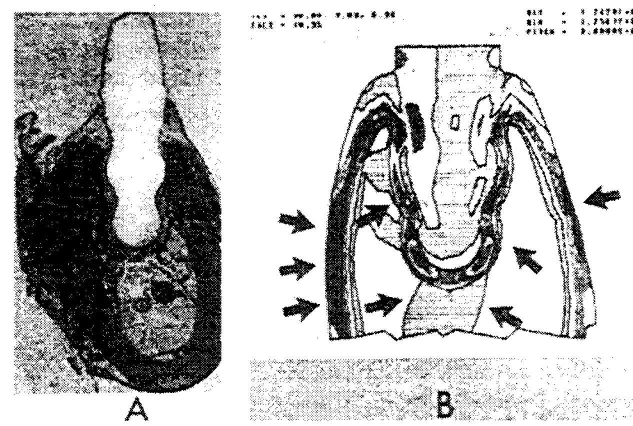


FIGURE 5 FIGURE 6

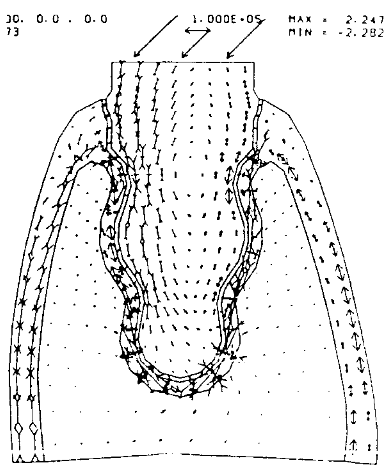
FIGURE 5
Zirconium oxide artificial root implanted in upper jaw of dog, 4 months postop, sagittal section. Successful fibrous tissue attachment and formation of alveolar bone proper resembling natural condition can be observed.

FIGURE 6
Cross section of artificial root implanted in mandible of dog (A) and Mises equivalent FEA pattern (B). Newly remodeling pattern of bone around root and cortical bone exactly coincides with FEA patterns.

Also, using Japanese monkeys, after four years of artificial root implantation without crown splint, and feeding of solid diet, the specimens were recovered. Microscopic observation was carried out. The bone and artificial roots were fused with fibrous tissue resembling periodontal ligament. Observation of a decalcified specimen 72 weeks and 4 years after implantation revealed that thin parallel fibrous tissue attaching to the root surface had turned into calcified tissue on which orthogonal fibrous tissues were anchored[4-8]. Calcified tissue resembling cementum was detected by microanalyzer and Fourier-Transmitted-Infrared (FTIR) analysis. At the surface of the artificial root, porous calcified substance deposited on which cementum-like tissue attached [4-8].

3.2. Finite element analyses relating to gomphotic and ankylotic apatite artificial roots - Comparison of stress distribution patterns around gomphotic and ankylotic roots.

Mises equivalent stress distribution patterns and principal stress trajectory patterns of gomphotic and ankylotic artificial roots of standard type (5mm in diameter) were compared (Figures 6B,7,10,11).



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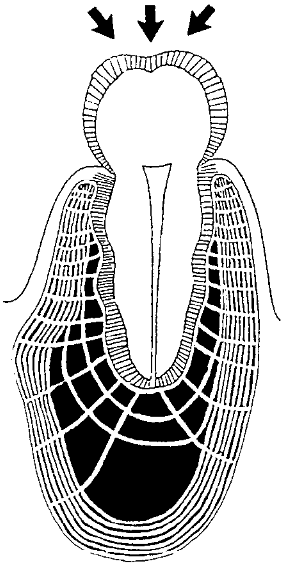


FIGURE 8

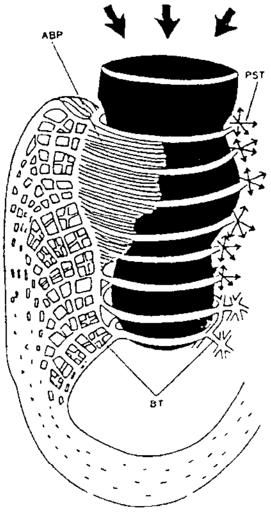


FIGURE 9

FIGURE 7

Principal stress trajectory (PST) pattern of gomphotic artificial root. PST was converted in periodontal fibrous tissue.

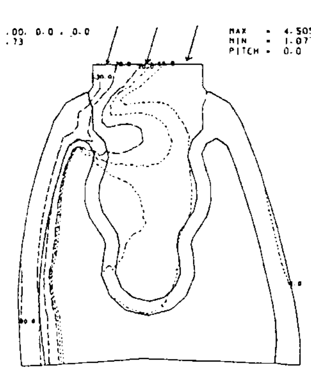
FIGURE 8

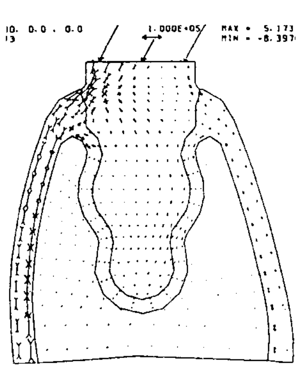
Two-dimensional schema of gomphotic tooth under repeated loading translated from FEA pattern of Figure 7. Biomechanical interactions between tooth and jawbone are shown in bone remodeling patterns.

FIGURE 9

Three-dimensional schema of gomphotic artificial root, translated from two-dimensional FEA pattern of Figure 7.

In the gomphotic artificial root model, stress distribution was equalized and mitigated by periodontal structures (Figures 5-7). The results were compared to histological findings of the specimens of animal experiments (Figures 5-7). The stresses were born mainly by cortical bone of the mandible through the alveolar bone proper. The orientation of principal stress trajectories in the artificial root was converted to two components, i.e. parallel and orthogonal to the root surface by periimplant fibrous tissue (Figure 7). The trajectories parallel to the root surface ran through the alveolar bone proper and ended in the cortex of the mandible (Figure 4). Orthogonal trajectories ran through the trabeculae, continuing with the alveolar bone proper and ending also in the cortex of the mandible (Figures 5-7). On the contrary, in the ankylotic artificial root model, stress distribution was not mitigated but concentrated in the artificial root and alveolar ridge of cortical bone in the mandible (Figures 10-12). Maximum and minimum values in the loading model of 45° inclination to the horizontal were 81.4MPa and 1.3MPa, respectively. Principal stress trajectories were demonstrated in which orientations in the artificial root ran continuously to osseous tissue attaching directly onto the root surface (Figure 11).





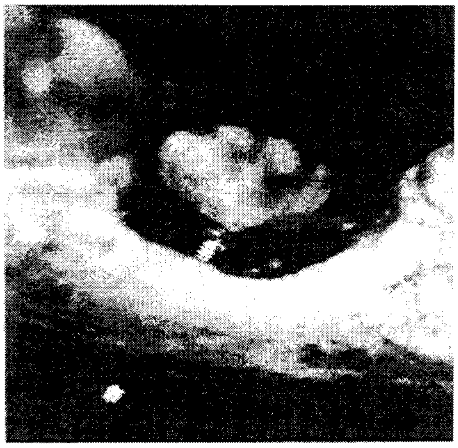
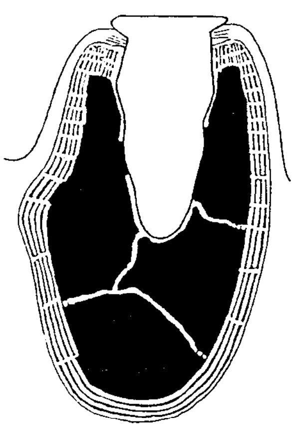


FIGURE 10 FIGURE 11 FIGURE 12

FIGURE 10
Mises equivalent stress distribution pattern of ankylotic artificial root.
FIGURE 11
Principal stress trajectory patterns of ankylotic artificial root.
FIGURE 12
Severe bone destruction observed around implant of osseointegration system similar to ankylotic artificial root, 6 years postop.

The results were compared to the findings of bone destruction in an animal experiment in similar condition (Figure 12). Although slight resorption and bone remodelling pattern around the implant were observed in the radiograph, severe bone destruction was detected in the specimen (Figure 12). The shape of the implant was slightly different from the analysis model; however, the bone destruction zone was assured to coincide with the site of stress concentration in Figures 10 and 11. Comparisons in FEA patterns with histological findings in either ankylotic or gomphotic artificial roots were found to coincide closely.

From these results, schemata of gomphotic are shown in Figures 8 and 9. Also schemata of the ankylotic in Figures 13, 14 without loading, and destruction of surrounding bone in the ankylotic artificial root after long-term function are shown in Figure 15.



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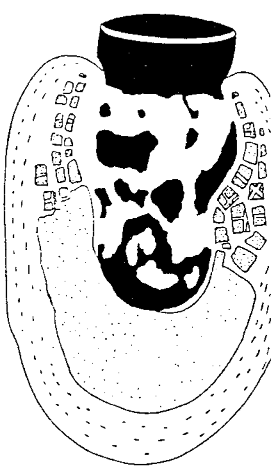

FIGURE 14

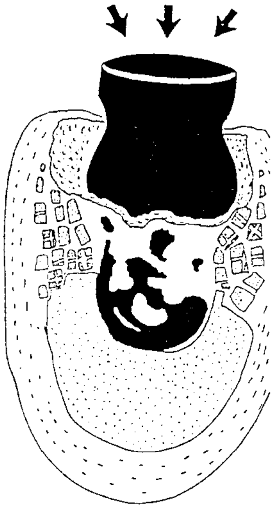

FIGURE 15

FIGURE 13
Two-dimensional schema of ankylotic or osseointegrated artificial root translated from FEA pattern of Figure 11. Without loading, ankylosis of bone to artificial root surface is quite restricted in observed specimens of Figure 3.

FIGURE 14
Three-dimensional schema of ankylotic artificial root without loading. Ankylosis takes place in restricted part of artificial root surface.

FIGURE 15
Three-dimensional schema of ankylotic artificial root under masticatory loading. Bone destruction coincides with stress concentration part of cortical bone analyzed by FEM Figures 10,11.

4. DISCUSSION

Recent research on artificial substitutions for mechanical supportive organs has been carried out concerning ankylosis or osseointegration between biomaterials and bone tissue. In studies on the functional effect, an ankylotic condition of the artificial root could be induced easily without loading after operations using newly tailored apatite artificial roots. However, without loading osseous tissue around the root, i.e., alveolar bone proper could not be induced. With mastication function, periimplant tissue resembling the original periodontal structures could also be induced around the tailored apatite artificial roots. These different conditions around the artificial roots could surely be induced with or without functional loading of mastication (Figures 2-4). From comparison of FE analysis patterns with histological findings in a gomphotic artificial root, osteogenesis for the alveolar bone proper and trabeculae coincided with the principal stress trajectories (Figures 5-9). Namely, parallel trajectories around the artificial root were assumed to form alveolar bone proper and orthogonal trajectories to form trabeculae attaching to the lamina dura, respectively (Figures 5-9). Osteogenesis (osteon formation) according to the principal stress trajectories is relevant to Wolff's law of functional adaptation in bone morphology[9]. The stress trajectory pattern was definitely dependent upon the artificial root form, jawbone morphology, and very little upon material constants of the bone and the artificial root. .

The most important gomphotic tooth system is ascertained to be the converting mechanism of the principal stress trajectories to parallel and orthogonal orientations to the root surface by periodontal ligament with sufficient microvessels. On the contrary, in an ankylotic root, principal stress trajectories orient continuously into ankylotic bone tissue from the artificial root (Figure 10,11,13-15). In mastication with severe repeated loading, the ankylotic or osseointegrated surface of the artificial root is assumed to be disrupted because of the differences in Young's modulus and Poisson's ratio between bone and biomaterials of the artificial root. The concept of osseointegration can not stand up to severe repeated loading for long-term function. Therefore, a new concept for a bone-bioceramics jointing system in severe loading conditions is necessary to be introduced instead of osseointegration.

A fibrous tissue jointing system is sure to be superior to ankylosis in severe loading. In the interface between bioceramics and bone tissue, there must be thin fibrous tissue with functional orientation and microvessels. The orientation of fibers around bioceramics is assumed to be dependent upon the principal stress trajectories, which are induced by the shape, Young's modulus, and Poisson's ratio of the artificial mechanical supportive organ (root or bone) under severe biomechanical loading. The binding of bioceramics with fibrous tissue can be carried out by calcified cementum-like tissue. The surface of bone connecting with bioceramics with fibrous tissue can continue remodelling with sufficient blood supplies from microvessels.

The jointing system of dental root to jawbone reflects on the function against mastication. The interface between different mechanical organs with different materials necessitates a specific juncture system under severe loading because of the disparity of material constants. The authors reported already the results of studies on the shape, material, and functional effect of artificial roots in functioning jawbone by means of finite element analysis[1-8]. From these studies, the following results and conclusions were obtained: The fibrous juncture system around bioceramics has an important role, after which the principal stress trajectories are converted.

The junction system of the mechanical supportive organ is divided into four major categories according to their functions: fibrous junction, cartilaginous junction, synostosis (osseous union), and synovial junction. These joint systems are consistent with the functional movement of each connecting skeletal bone. Fibrous joints, for example, syndesmosis (tibiofibular), suture (skull), and gomphosis (tooth) or fibrocartilagious, i.e., symphysis (vertebral bodies), are an important joint system to develop a ceramics-bone juncture system. Regarding the junction of bioceramics with original bone, which have quite different material constants of Young's modulus and Poisson's ratio from each other, synostosis cannot be obtained under severe loading conditions [3].

Conventional research on dental implants has been carried out mainly to study the component effect upon tissues. However, mechanical supportive organs such as artificial roots have essentially a close correlation between their form, component, and function which exerts a biomechanical effect upon surrounding tissue. The jointing system of the tooth to the jawbone is closely relevant to the function of the tooth. Concerning tooth crown function for mastication, we observed the movements of tearing, cutting, and grinding which exert multiple forces on the root. The dynamic factor in occlusion is motion, which necessarily means jaw motion (8). Three basic types of jaw motion in mammals are known: (a) Orthal, (b) Propanial, and (c) Ectenal (8). According to G.G.Simpson, he basic principles of occlusion seem to be four: (a) Alteration or Interlocking, (b) Opposition, (c) Shearing, and (d) Grinding[10].

Phylogenic and evolutional studies of the viscerocranium revealed that a gomphotic tooth with occlusal function has the ability in the jawbone to counteract against the multiple forces of mastication. On the contrary, an ankylotic tooth can be found in lower animals (reptiles), whose teeth have no masticatory but prehensile function. The ankylotic reptile tooth system is homodontic and polyphyodontic. Ankylotic bone tissue breaks down after a certain period of prehensile function. Therefore, new polyphyodontic teeth begin to erupt. Osseointegrated implants or ankylotic roots have no countermovement against multiple forces.

Conventional dental implants were invented with a concept of implantable denture, but not that of an artificial organ. The most serious problems of dentures are mobility and falling out from the jaws. Therefore, the main purpose of an implantable denture is fixation in the jawbone so as to prevent postop falling out. Almost all dental implant shapes are devised from the standpoint of postop fixation. On the contrary, the main function of the original tooth system is the bearing of multiple masticatory forces.

Therefore, for artificial roots the shape for bearing masticatory force is more important than fixation. The authors have already reported on the shape and material effect of artificial roots on surrounding tissues[1-8]. From the research, stress distribution is definitely dependent upon the artificial root shape and jawbone morphology. Periimplant tissue formation resembling periodontal structures is almost dependent upon both shapes but very little upon the material property. From these experiments and analyses, the authors concluded that the tooth is a vehicle of multiple masticatory forces by which stresses are mitigated and equalized[1]. The stress orientations are converted by periodontal root supporting structures, after which stresses are transmitted to cortical bone of the jaw. The cortex must bear these stresses. If a stress converting system in or around the artificial root is not formed, implant failure in the artificial root and/or surrounding bone can surely occur after long-term function.

5. CONCLUSION

From short-and long-term histological study of the functional effect of artificial roots upon surrounding tissue, the juncture of artificial roots with periimplant tissue is found dependent upon the functional micromovement of the artificial root after operation. From FEA on the functional effect of artificial roots and animal experiments, the following results were obtained:

(1) a. In the functional group, gomphotic juncture of artificial roots with bone resembling alveolar bone proper was observed.

b. In the nonfunctional group, ankylosis of artificial roots with cortical bone was observed without bone formation around the root.

(2) a. In a gomphotic artificial root under loading, mitigated stress was distributed evenly in alveolar bone proper and cortical bone of the jaw, and principal stress trajectories were converted to parallel and orthogonal elements in periimplant fibrous tissue.

b. In an ankylotic artificial root under loading, principal stress trajectories oriented continuously into ankylotic bone tissue, and concentrated stress was distributed in ankylotic part of the artificial root and cortical bone, where sever bone destruction occurs after long-term function.

(3) Through integrated triad research on shape, component, and functional effect, a gomphotic tooth is known to be a vehicle of multiple masticatory forces.

(4) Ankylotic tooth root system is of antinomy. Only without loading ankylosis takes place. On the contrary, under severe loading ankylosis between bone and ceramics disrupts because of differences of material constants. Therefore, ankylotic artificial root can stand up only under condition without functional loading.

(5) Under severe long-term loading functions, a new concept for a bone-bioceramics jointing system, i. e., fibrous tissue juncture, is necessary