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BIOMECHANICAL RESEARCH ON JUNCTION SYSTEM OF BONE WITH BIOMATERIALS

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Abstract—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 be obtained under severe loading conditions. Therefore, it is necessary to introduce a new junction system for the interface between the biomaterial mechanical organ and original bone. 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 already reported the result of studies on the shape effect of artificial roots in functioning jawbone by means of finite element analysis.

Studies on the functional effect of artificial roots in undulated shape were carried out biomechanically by means of finite element analysis using models to investigate an effective juncture system between bone and biomaterials. The results of finite element analysis were compared with the findings obtained from histological specimens.

To observe the juncture state of bioceramics with tubular bone cortex, tubular apatite artificial bone was implanted in the femur of a dog.

From these studies, the following results and conclusions were obtained: (a) The fibrous juncture system around bioceramics has an important role, after which the principal stress trajectories are converted; and (b) optimal undulated morphology compatible to the artificial bone's juncture system by means of fibrous ligament is essential for remodeling of the bone around the artificial skeletal bone.

Key Words—junction system, material property, functional effect, finite element method, principal stress trajectory

INTRODUCTION

THE JUNCTION system of the mechanical supportive organ is divided into four major categories according to their junctions: fibrous junction, cartilaginous junction, synostosis (osseous union), and synovial junction. These joint systems are consistent with 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 (1). Therefore, it is necessary to introduce a new junctional system for the interface between the biomaterial mechanical organ and original bone, which enable to remodel the bone tissue continuously (1–3). Bone and teeth not only have unique biomechanical and biological characteristics, but also a special junctional morphology, i.e., the bone/bone and bone/tooth interface.

As already reported, an artificial root made of sintered dense hydroxyapatite (apatite) was developed, which has a different binding system (fibrous tissue attachment gomphosis) with the jawbone compared to conventional dental implants (ankylosis or osseointegration) (4–8).

The bone and tooth have a triad of correlation between morphology, component, and function (5,9). They have a morphological optimization system with a stress-dispersing adaptive capacity effective over a long span of time involving many generations (1). Therefore, triad research studying the material, shape, and functional effects upon surrounding tissues is essential in investigating an artificial joint, bone, and root capable of substitution for the original organ. The bonding 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 (1,2). The result of the shape and material effect of artificial roots on surrounding tissues were already reported (1,2,3). In this paper the functional effect of artificial roots was studied biomechanically by means of the finite element method (FEM) to investigate an effective juncture system between bone and biomaterials (1–3). To observe histologically the functional effect of an artificial root, animal experiments using dogs were carried out, and masticatory loading against artificial roots was applied postoperatively. The authors have carried out histopathological studies on periartificial-root tissue formation to observe the interaction between bone and an artificial root made of sintered hydroxyapatite (4–6). As a result, a fibrous juncture state of artificial root with bone was obtained (4–6). The bone formation around the artificial root observed in specimens coincided with the principal stress trajectories analyzed by FEM (1–3).

The tubular apatite artificial bone was also implanted in the femur of a dog to observe the juncture state of tubular bioceramics with bone cortex (7). Then the results of finite element analysis (FEA) with the findings from histological specimens were compared. As a result, a fibrous juncture state of apatite artificial bone with cortex was observed. The fibrous juncture system around the bioceramic bone and root have 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, the fibrous junction system to join an artificial ceramic organ with surrounding bone was studied. From the standpoint of juncture function, tissue reaction, and stress carrying shape, the criteria required for artificial substitution of mechanical supportive organs are concluded as follows: Material biocompatibility is necessary to induce tissue resembling the natural condition around it. The undulated morphology is compatible with its functions in relation to stress distribution in the surrounding bone. Biofunctional junctioning with fibrous ligament between biomaterials and natural bone is required, after which remodeling of bone can continue long term.

METHOD AND MATERIALS

Animal Experiment

Apatite artificial roots. Artificial roots of fibrous tissue attachment type made of dense apatite were implanted in adult dogs. For the nonfunctioning group, the roots were implanted deeply at the level of the gingival. Then the dogs were fed a soft diet. For the functioning 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 (3, 6, 8, 12, 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.

Tubular apatite artificial bone. Tubular apatite artificial bone (20% porosity) was implanted in the femur of an adult dog to observe whether apatite bone becomes ankylotic or not. The femur with the implant was fixed with an A-O plate. Twelve weeks after implantation, decalcified and undecalcified specimens were prepared and evaluated microscopically.

Finite Element Analyses Relating to Gomphotic and Ankylotic Apatite Artificial Root

Comparison of stress distribution patterns around gomphotic and ankylotic roots was carried out. The model for FEA and the experimental conditions have already been described (2).

The stress distribution around newly tailored artificial roots of standard type, 5 mm in diameter, of gomphotic and ankylotic conditions was analyzed in implantation models by FEM. The models of the mandibular molar region with artificial roots implanted were made in the plane stress state.

Based on results obtained from these experiments, a new juncture system of the stem of an artificial joint with undulated tubular artificial bone was developed.

RESULTS

Animal Experiments

Apatite artificial roots. Nonfunctioning Group—Observation of undecalcified specimens 3 weeks to 12 weeks after implantation revealed that the artificial roots were ankylotic, namely, in direct contact with surrounding bone tissue, which had no tooth supportive, structure, i.e., periodontal ligament and alveolar bone proper with trabeculae. Until osseointegration was obtained, no masticatory loading was applied. After osseointegration was obtained, applying long-term function, severe bone destruction was observed around the ankylotic artificial root (2).

Functioning group—Observation of undecalcified specimens 6 and 8 weeks after implantation revealed that the artificial roots were in direct contact with fibrous tissue, and bone formation occurred resembling alveolar bone proper with trabeculae (4–6). The bone and artificial roots were fused with fibrous tissue resembling periodontal ligament (4–6). Observation of a decalcified specimen 72 weeks after implantation revealed that thin parallel fibrous tissue attaching to the root surface turned into calcified tissue on which orthogonal fibrous tissues were anchored (4–6). At the surface of the artificial root, porous calcified substance was deposited, on which cementum-like tissue attached (4–6,9).

Tubular apatite bone was implanted in the femur of a dog. During fixation, no fracture was observed postoperatively. The specimens were recovered 12 weeks postop (Fig. 1). Although bone marrow formation was observed in the implanted tubular apatite artificial bone, no ankylosis of the tubular apatite bone with surrounding osseous tissue but fibrous tissue attachment was observed in the femur.

Finite Element Analyses Relating to Gomphotic and Ankylotic Apatite Artificial Roots

Mises equivalent stress distribution patterns and principal stress trajectory patterns of gomphotic and ankylotic artificial roots of standard type (5 mm in diameter) were compared (Figs. 2 and 4). In the gomphotic artificial root model, stress distribution was equalized and mitigated by periodontal structures (Fig. 2). The orientation of principal stress trajectories in the artificial root was converted to two components, i.e., parallel and orthogonal trajectories to the root surface by periimplant fibrous tissue (Fig. 2). For the conversion of the principal stress trajectories, undulated form had a very important role. The results were compared to the histological findings of the specimens of animal experiments (Fig. 3). These findings coincides with the results of FEA. From the specimen findings and stress distribution patterns

FIG. 1. Tubular apatite artificial bone was implanted in femur. Bone marrow was derived in tubular apatite bone.

obtained by FEA, it was understood that the stresses were carried mainly by cortical bone of the mandible through alveolar bone proper and the trajectories parallel to the root surface ran through the alveolar bone proper and ended in the cortex of the mandible. Orthogonal trajectories ran through the trabeculae, continuing with the alveolar bone proper, and were assumed to end also in the cortex of the mandible.

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. Principal stress trajectories were demonstrated in which orientations in the artificial root ran continuously to osseous tissue attaching directly onto the root surface (Fig. 4). The results were compared to the findings of bone destruction in an animal experiment in a similar condition (Fig. 5). Although slight absorption and a bone remodeling pattern around the implant were observed in the radiograph (1), severe bone destruction was detected in the specimen. The shape of the implant is slightly different from the analysis model; however, the bone destruction zone is assumed to coincide with the site of stress concentration in Fig. 4.

Comparisons in FEA patterns with historical findings in both ankylotic and gomphotic artificial roots were found to coincide closely.

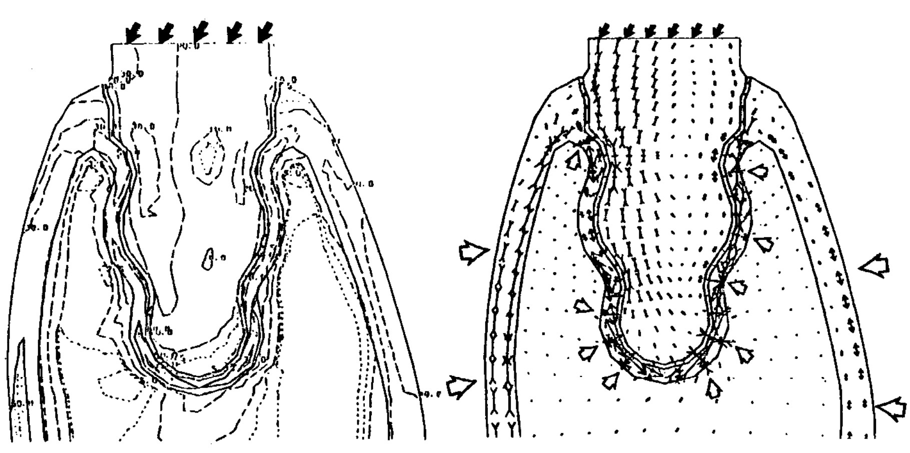

FIG. 2. FEA pattern of gomphotic artificial root. Upper: Mises equivalent stress distribution pattern; Lower: Principal stress trajectory pattern.

FIG. 3. FEA pattern of ankylotic artificial root. Upper: Mises equivalent stress distribution pattern; Lower: Principal stress trajectory pattern.

Based on the aforementioned results, a biomechanical system of the tooth was resolved (Fig. 6). Also a new system of a stem with a fibrous juncture system and undulated tubular form was devised (Fig. 7).

DISCUSSION

A research on artificial substitutions for mechanical supportive organs has been carried out recently concerning ankylosis or osseointegration between biomaterials and bone tissue (8). In studies on the functional effect, an ankylotic condition of the artificial root could be induced without loading after operations using newly tailored apatite artificial roots. With mastication function, peri-implant tissue resembling the original periodontal structures could

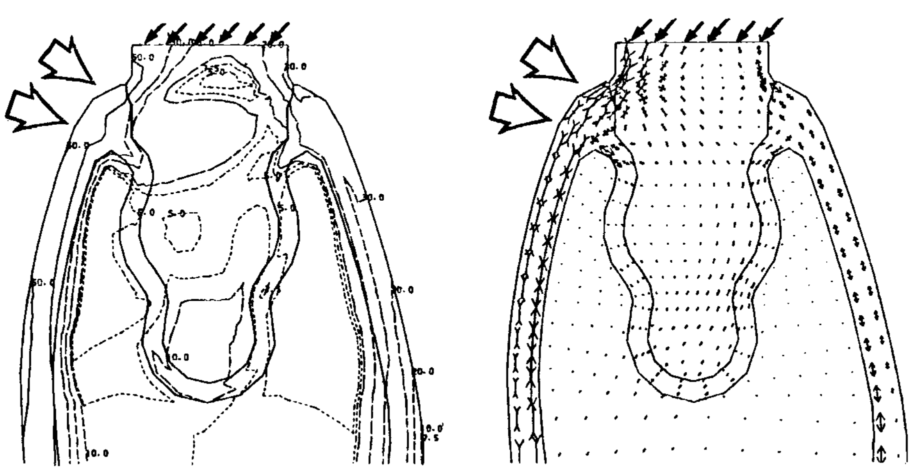

FIG. 4. Histological finding of gomphotic artificial root.

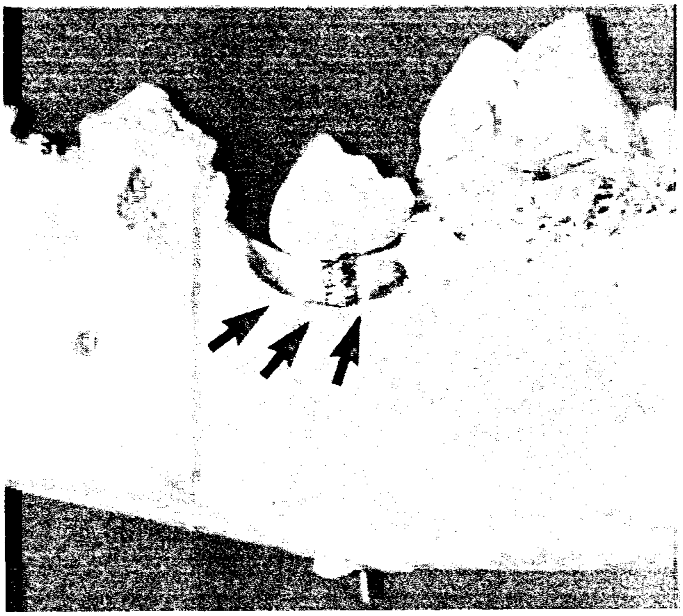

FIG. 5. Bleached bone specimen of osseointegration artificial root.

also be induced around the tailored apatite artificial roots. These different conditions around the artificial roots could be induced with or without functioning load of mastication. From comparison of FEA patterns with histological findings in a gomphotic artificial root, osteogenesis of the alveolar bone proper and trabeculae coincided with the principal stress trajectories (Figs. 2 and 3). 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 (Figs. 2 and 3). Osteogenesis (osteon formation) according to the principal stress trajectories is relevant to Wolff's law of functional adaptation in bone morphology (10–16). The stress trajectory pattern was definitely dependent upon the artificial root form and juncture system.

The most important gomphotic tooth system is assumed to be the converting mechanism of the principal stress trajectories to parallel and orthogonal orientations by periodontal ligament (Fig. 3). Especially, undulated form can convert the principal stress trajectories parallel and normal, which can be effective to maintain remodeling of the bone (Fig. 2). On the contrary, in an ankylotic root, principal stress trajectories concentrate in the cortex and orient continuously into ankylotic bone tissue from the artificial root (Fig. 4). In mastication with severe repeated loading, the ankylotic or osseointegrated surface 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. The concept of osseointegration cannot stand up to severe repeated loading (1). Therefore, a new concept for a bone-bioceramics jointing system in severe loading conditions is necessary to be introduced (1).

A fibrous tissue jointing system is assumed 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. 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 biomaterials under a loading condition. The binding of bioceramics with fibrous tissue can be carried out by calcified, cementum-like tissue (4–6,9). The surface of the bone facing bioceramics connected by fibrous tissue to each other can continue remodeling.

From this research, it was proved that stress distribution is definitely dependent upon the artificial root shape in a gomphotic root. Peri-implant tissue formation resembling periodontal structures is almost completely dependent upon shape but very little upon material property. Based on results obtained from these experiments and analyses, the authors disclosed the mechanical property of the gomphotic tooth system from the standpoint of biomechanics and morphology (Fig. 6) and developed a new juncture system of the stem of an artificial joint with undulated tubular form (Fig. 7). In tubular artificial bone, bone marrow can be induced and principal stress trajectories are converted by undulated form favorable for tubular cortical bone remodeling.

CONCLUSION

From FEAs on gomphotic and ankylotic artificial roots and animal experiments, the following conclusions were obtained:

1. In fibrous junction artificial root with undulated form, stress distributing around the root was mitigated and principal stress trajectories were converted to parallel and orthogonal elements in periimplant fibrous tissue. By this mitigation and stress trajectory conversion, osseous tissue remodeling can be maintained in jawbone.
2. In an ankylotic artificial root, principal stress trajectories oriented continuously into ankylotic bone tissue, and stress concentrated in alveolar cortical bone. By this stress concentration, bone remodeling cannot be maintained.
3. In severe loading conditions, a new concept for a bone-bioceramics jointing system of

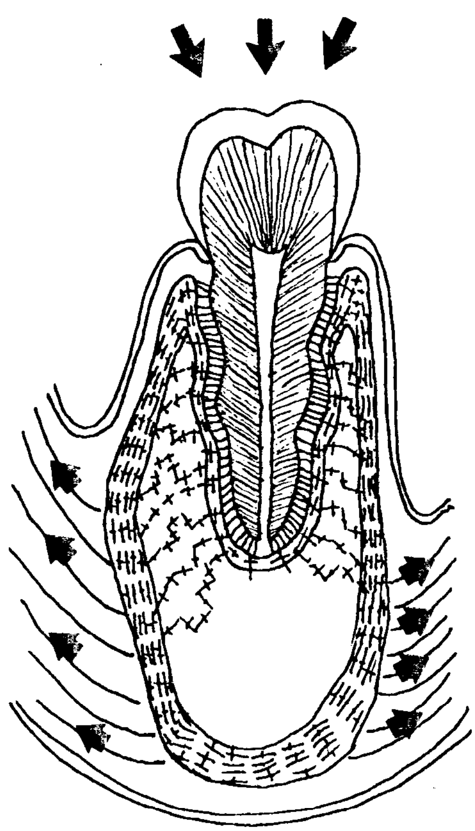

FIG. 6. Biomechanical system of the tooth.

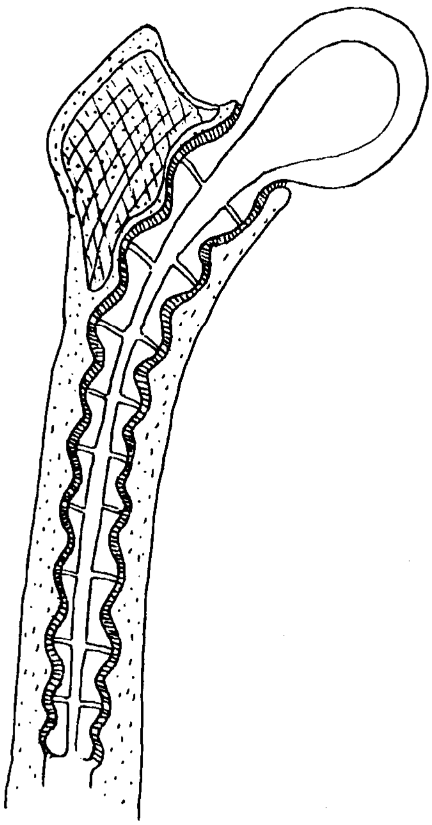

FIG. 7. New system of stem with fibrous juncture system and undulated tubular form.

a tubular undulated stem with fibrous tissue junction is necessary to be introduced instead of osseointegration or ankylosis.

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