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Use of Micro Computed Tomography in Prosthetic Dentistry

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Review

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ABSTRACT

Today, the use of micro-computed tomography is becoming widespread in almost every field of dental research. When the national review articles on micro-computed tomography are examined, it is seen that the focus is on endodontic and surgical dental applications. As prosthodontists, our article, which was compiled in order to deepen the specific usage areas of micro-computed tomography applications and to review the studies done in this area, provides information about the use of micro-computed tomography method in prosthetic dentistry. Micro-computed tomography is a powerful *in vitro* research method. Micro-computed tomography was used; marginal and internal compatibility of restorations, cement spacing of restorations, adaptation of denture bases, accuracy of prosthetic measurements, effects of occlusal irregularities, volumetric changes in teeth due to dental post application, biomechanical evaluation of implant-abutment connection, and compatibility of maxillofacial prostheses.

Keywords: Computed Tomography, Dental Implant, Marginal and Internal Fit, Maxillofacial Prostheses.

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Introduction

Since the discovery of X-ray by Rontgen in 1895, technology has revolutionized diagnostic medicine, making it feasible to examine the internal structure of the body in a non-invasive way.[1] This method provided a breakthrough in diagnosis and treatment in the field of medicine and pioneered other methods. Computed tomography (CT) is the product of combining X-ray with computer technology. Imaging with CT was first developed in the early 1970s. The microtomography system was first developed by Jim Elliott in 1980, and a small tropical snake was investigated with 50 µm resolution for the first time.[2]

The X-ray passes through the object being examined and the images obtained are two-dimensional (2D). When the object is exposed to x-rays from different angles, images can be converted into three-dimensional (3D) images using computer algorithms. Some frames are reached when the images on CT devices are enlarged. These frames are made up of voxels and pixels, which in turn make up the image. A pixel defines a point in 2D. The voxel, on the other hand, is a unit volume and adds a third dimension to the digital image element, the pixel.[3] The volume elements (voxels) used in clinical CT pictures are typically 1 mm^3 in volume, however X-ray micro-CT systems provide far superior spatial resolution and generate voxels that are 1,000,000 times smaller in volume than CT voxels.[4,5] The large number of sections taken from the sample increases the image resolution achieved by obtaining more detailed information from the sample.[2] Micro-CT devices are similar in structure to CT devices. However, there are two main differences between micro-CT devices and CT devices. First, in CTs, the X-ray source and detector rotate around the patient, which causes mechanical vibration. However, in micro-CT, the x-ray source and detector are generally stationary, while the small object is rotated around its axis. Thus, vibration decreases and resolution increases. The second difference is in CTs the X-ray source size is 1 mm but in micro-CT the size is 5-50 µm. The smaller the source increases the projection depth. Images can be evaluated qualitatively and quantitatively.

In many views, images are rebuilt to create 3D spatial distribution maps of attenuated materials or material density within tissues like teeth.[6] By comparison, conventional radiography was restricted to providing 2D images representing the amount of material attenuation along the X-ray track. The process of creating 3D images that show the examined structures in more detail by using various computer programs from microtomographic data is '3D reconstruction', which is expressed as reconstruction. High-resolution detectors and a microfocal X-ray source (90–150 kVA) are used in micro-CT systems to recreate the materials' 3D surfaces. Allows rotated projections along multiple viewing directions. The images symbolize spatial distribution maps of linear attenuation parameter specified by the atomic composition of the sample and the energy of the X-ray source. Since the imaging technique does not devastate the samples, both internal and external features of the same sample can be inspected more than once.

Micro-CT can be used to directly investigate a wide range of samples, including materials like ceramics, polymers, biomaterial infrastructures, and mineralized tissues like teeth and bones. Soft tissues, such as the lungs, that have been infiltrated or perfused with a contrast agent that has a higher density than the surrounding tissues can also be examined using micro-CT imaging. The latest generation of micro-CT systems enables *in vivo* imaging of small live animals.[8,9] The micro-CT device, which also finds use in dentistry, has taken its place in the majority of dental research. This article's goal is to review the use of micro-CT in research on prosthetic dentistry.

1. Micro-CT Usage Areas in Prosthetic Dentistry

1.1. Evaluation of marginal and internal fit of restorations

The long-term clinical success of fixed partial dentures is also evaluated by the compatibility of the restoration with the supporting structures. Marginal discrepancy lead to microorganism accumulation and soft tissue proliferation[10]; these cause biological problems (inflammation, etc.). Biological problems are more common than mechanical problems among the reasons for the replacement of prosthetic restorations.[11] Marginal discrepancy lead to plaque accumulation, increasing the risk of caries in the abutment teeth.[12] Deficiencies in the marginal fit of the crown (>120 µm)[13] will result in microleakage and rapid dissolution of the cement. As a result, biological complications such as pulpitis, secondary caries and periodontal problems will occur in the future. Marginal and internal fit is assessed with the following techniques. It is possible to perform examination using the silicone replica technique, clinical examination with the probe, which is a qualitative evaluation, examination with bite-wing x-rays, 2D examination with stereomicroscope and micro-CT. With the micro-CT method, it is possible to make measurements that can be repeated from many points without damaging the restoration, abutment tooth or cast model.[14] There are studies assessing the marginal and internal fit of different production techniques, different step types, different preparation techniques, various prosthetic materials and designs with micro-CT.

In a study in which marginal fit of various In-Ceram alumina ceramic cores produced with four different techniques (Wol-Ceram, Slip cast, Celay) were evaluated, micro-CT was preferred as examination method, marginal space and marginal discrepancy were tested mesiodistally and buccolingually with micro scale.[15] Unlike production techniques influenced the marginal fit of full-ceramic restorations. The slip-cast method and the Wol-Ceram system showed the greatest marginal fit, pursued by the Cerec inLab with clinically satisfactory results.

Borba *et al.*[16] used a novel approach based on micro-CT technology to assess the marginal and internal fit of zirconia-based all-ceramic three-unit fixed partial dentures (Y-TZP - LAVA). Five measurement points were selected for micro-CT scans: marginal gap; chamfer step area; axial wall; axio-occlusal transition area; occlusal area. Significant differences in gap width were observed between the evaluated measurement points. The marginal gap exhibited the smallest gap size. The occlusal area had the largest gap size, pursued by the axio-occlusal transition area point. Chamfer step area and axial wall gap size values were found to be statistically comparable. It was therefore able to draw the conclusion that varying degrees of adaptation were seen in fixed partial dentures at various measurement points.

Demir *et al*.[17] preferred micro-CT as the examination method before and after cementation in a study where they evaluated the marginal gap and marginal mismatch of all-ceramic crowns with chamfer and shoulder finish line styles. Samples are sectioned into two groups according to the finish line design: shoulder and chamfer. All-ceramic crowns are further grouped by type: Feldspathic, aluminum oxide ceramic system and Lithium disilicate press ceramic system. Prior to cementation, five crowns from each group were examined with micro-CT in sagittal and coronal section to detect marginal gap and marginal discrepancy values for four different areas of the crown. Scanning was repeated after cementation and thermal cycling. As a result of the study, all-ceramic systems revealed clinically admissible marginal adaptation rates. The Feldspathic ceramic system revealed minimum overall change, exception for the marginal gap rates of the coronal mesial area.

In the study evaluating the marginal and internal adaptation of crown copings produced from three various materials, nickel-chromium alloy, zirconia and lithium disilicate, micro-CT was preferred to acquire volumetric reconstructions from every sample.[14] It was determined that the casting metal alloy showed the greatest overall marginal fit and lithium disilicate the best general internal fit. General evaluation of the results revealed that all materials tested were within the clinically accepted level despite significant differences in compliance.

Kim *et al*.[18] aimed to measure the marginal and internal fit of lithium disilicate crowns produced from digital and traditional impressions with micro-CT. The CS3500 intraoral digital impression system, Trios intraoral digital impression system, Ceramill Map400 extraoral digital impression system, and heat-press process were used to create lithium disilicate crowns. Within limitations of this investigation, the results show that the fit of lithium disilicate crowns made using digital techniques is equivalent to the traditional heat-press technique for clinical usage. IPS e.max CAD crowns fabricated using the CS3500 intraoral scanner revealed considerably better marginal fit than those of the other 3 groups and there was only a small internal mismatch relative to the Trios scanner. Between IPS e.max Press crowns produced with the heat-press method and IPS e.max CAD crowns produced utilizing the extraoral scanner and Trios intraoral scanner, no difference in marginal or internal fit were found.

Micro-CT was preferred as the examination method in the study in which the marginal fit of Co-Cr alloy copings manufactured with traditional casting and 3 different CAD/CAM were evaluated.[19] Two different commercial alloy systems were used for each production technique. The milling and selective laser melting groups displayed considerably higher marginal discrepancy than the comparison groups, while the milling/sintering groups displayed significantly lower rates than the control group. Milling groups showed considerably higher marginal discrepancy than comparison groups. In selective laser melting and milling/sintering groups, marginal mismatch rates are material typical. However, the milling/sintering groups showed approximately equivalent or less marginal discrepancy with the comparison groups. According to the results of this *in vitro* micro-CT revealed that the marginal adaptation rates of the Co-Cr largely depend on the production processes and sometimes the alloy types.

In a study evaluating marginal and internal fit of lithium disilicate inlays fabricated with two different axial milling systems and conventional method probable gaps in different areas were analysed.[20] As a result, different manufacturing methods had an impact on the internal and marginal fit of inlays. The conventional group demonstrated the greatest marginal and internal fit outcomes; even so, all samples in each group were within the clinically reasonable marginal range limit. Among the CAD/CAM groups, the five-axis system showed preferable axial-internal fit and occlusal-marginal fit rates than the three-axis system.

Micro-CT was preferred as the examination method in the study, which evaluated the external (vertical and horizontal) and internal adaptation of implant crowns produced with four different production techniques and reported that the best results belong to the CAD/CAM production technique.[21] In the statistical analysis, it was seen that there was no important difference among the groups for vertical discrepancy. While there was no important difference for internal and marginal discrepancy in conventional casting groups, it was observed for CAD/CAM milling group.

Duqum *et al*.[22] aimed to investigate the marginal fit of all-ceramic crowns constructed of lithium disilicate and zirconia with micro-CT using two different manufacturing processes of CAD/CAM. Both workflows are legitimate techniques for the producing of monolithic ceramic restorations. Lithium disilicate or zirconia crowns' marginal match was not improved by printed model. Regardless of which workflow was used to achieve the restoration, both materials have clinically acceptable marginal fit.

Micro-CT was preferred as the examination method in the study in which the marginal and internal adaptation of full-ceramic inlays designed using three different CAD systems (CEREC, Dentsply Sirona, York, PA; KaVo, Everest, Germany and Planmeca, Helsinki, Finland) were evaluated.[23] A total of 363 measurements were made, 11 measurements for each sample. In the study, it was found that the software programs of different systems affect the marginal and internal adaptation of inlays.

Ekici *et al*.[24] aimed to evaluate the marginal and internal fit of full-ceramic crowns and inlays manufactured using two intraoral scanners and a model scanner with micro-CT. For local linear measures on full-ceramic crowns, there was often no variation between scanners, although gaps were more noticeable in restorations performed with intraoral scanners for volumetric measurements. But when the inlay repairs were examined, there were noticeable variations amongst the groups. The marginal and internal gap of both crowns and inlays showed average rates that could be considered clinically acceptable.

In a study aimed to evaluate external gap progression in three dimensions after chewing simulation of highly translucent zirconia and zirconia-enhanced lithium silicate with different preparation design applied to endodontically treated teeth. The external gap progression of the adhesive overlay and full crown models prepared on the enamel-cementum border of the molar teeth was evaluated in three dimensions before and after the chewing simulation. The full crown preparation design was found to have a considerably lower gap process regarding the overlay preparation. Zirconia-enhanced lithium silicate exhibited significant inferior gap progression compared to highly translucent zirconia. Preparations restored with zirconia-enhanced lithium silicate appear to perform better in sealing the external margin after cyclic fatigue.[25]

Tamam *et al*.[26] evaluated the fit of CAD-CAM ceramic restorations following different preparation procedures with micro-CT. In the study, monolithic feldspathic ceramic crowns with a total of 28 anatomical contours were produced for 4 tipodont teeth. The preparation groups are as follows: finishing with extra coarse (181 µm) diamond rotary instrument (EC), extra coarse grain diamond rotary instrument followed by fine grain (40 µm) grinding with diamond rotary instrument (F), extra coarse grain and fine grain diamond after finishing with rotary instrument, finishing with extra fine (20 µm) diamond rotary instrument (VF) and polishing with rubber (P) after all process steps have been applied. Micro-CT scanning was preferred to determine the gap among tipodont teeth and crowns. 196 measurements were taken, and reference points including the margin, chamfer, tubercle tips, and central fossa were identified. In all areas, the extremely coarse grained diamond rotary instrument group resulted in the largest gap values. The lowest interval value at the marginal area was seen in the P group. As a result of the study, it was seen that for monolithic feldspathic CAD-CAM restorations, the surface finishing technique with fine grained rotary instruments provided greater marginal fit.

1.2. Evaluation of cement space of restorations

The grade of the marginal fit and the thickness of the bonding material are among the factors affecting the durability of ceramic restorative materials.[27] Another factor in the endurance of restorative material is the gap filled with cement in the 3D plane between the restoration and the tooth surface. In general, 3D adaptation is direct impacted by the thickness of the cement layer. A restoration's internal and marginal cement thickness can be measured using techniques like sectioning, silicon replica, or micro-CT. Among the various techniques used to evaluate the cement thickness of dental restorative materials, micro-CT is more widely used due to its ability to perform quantitative analysis, repeatability at different time intervals without damaging the samples.[14,28]

Micro-CT technique was used in the study to evaluate the marginal and internal cement thicknesses of inlay restorations produced of different CAD/CAM materials, and the restorations were found to have clinically acceptable cement thickness.[29]

In the study investigating the effects of two different cement (Panavia, Variolink II) systems with different cement thicknesses on full-ceramic crowns on the stress distribution between the crown and the core, micro-CT was preferred as the examination method.[30] Cement with a greater elastic modulus resulted in reduced tensile stress in the crown and core layers, and the shear strength of the cement was found to be critical to the strength of the full-ceramic crown. Evaluation of different cement space has shown that there is an ideal thickness that can minimize the stress level in full-ceramic crowns; however, it has been stated that the cement thickness is of minor effect on the stresses in the core or crowns.

Al-Saleh *et al*. evaluated the microleakage and fracture stresses of full-ceramic veneers bonded with traditional polymeric resin (Multilink N) and two different polymeric bioactive cements (ACTIVA, Ceramir) in order to assess their color stability.[31] According to the type of cement used, all produced samples were randomly separated into three groups. All samples were aged for 30,000 cycles. This samples were used to check with a micro-CT for microleakage. Relative to Multilink N and ACTIVA, Ceramir exhibited the most microleakage.

1.3. Evaluation of adaptation of denture bases

Full dentures and removable partial dentures continue to be a frequently applied treatment option for partially or totally edentulous patients. One of the most significant factors determining the performance of these prostheses is the fit of the base of the prosthesis to the mucosa and the retention provided when the gap between the base and the tissues is as small as possible.[32] The fit of the denture base may vary according to different production techniques or the applied arch. Denture base fit has been frequently examined using various methods such as stereomicroscopic space quantification of denture bases by taking sections on the plaster model, measurement of the physical mass or thickness of the elastomeric impression material positioned between the denture base and the plaster model, and digital superimposition analysis.[33-35] All these procedures assessed fit by examining the space between the denture base and the plaster model representing the underlying mucosa. Micro-CT, a technique often employed in dental research, can visualize internal structures without damaging the structures with 3D imaging and can not only take linear and yet also volumetric assessments of space among or within materials.[36] This modern method can be a useful tool for evaluating denture base adaptation.

Micro-CT method was used in the study in which the fit of denture bases produced with four different production methods (conventional pressure, conventional injection, PMMA milling method and 3D printing method) was evaluated.[37] In this study, 3 areas in the mandible and 6 areas in the maxilla were measured to assess the denture base adaptability. It has been found that denture bases milling from PMMA show greater adaptability for both maxillary and mandibular jaws than 3D printing or conventionally fabricated denture bases.

1.4. Evaluation of the accuracy of prosthetic impression

The correct and clear impression of the tooth prepared to be restored should be taken. Conventional and digital methods are used in the impression process. The conventional impression is to obtain the negative with various impression materials to replicate the surface contour of the prepared tooth, its connection with adjacent teeth and soft tissue. Although this technique is considered the gold standard for providing precise and reliable details concerning patients' intraoral conditions[38], it has many disadvantages such as cumbersome procedures, dependence on the skill and experience of the clinician, and storage problems. The digital impression is produced indirectly by scanning the traditional impression, the plaster model produced from the conventional impression, or by direct scanning of the prepared tooth with an intraoral scanner. Compared to traditional systems, digital impression systems have advantages such as increased patient satisfaction, decreased time and expense performance, reduction of errors due to volume changes and user-related mistakes, material savings and a cleaner environment.[39] It has also been reported that digital impression accuracy is similar to conventional impression.[40] Restorations can be produced directly via CAD/CAM systems using digital impressions, and the restoration is often completed in a single appointment. In another workflow, the model obtained indirectly from a conventional impression or impression is scanned and its data is transferred to electronic media and restorations are produced in the laboratory.

Li *et al*.[41] obtained a three-dimensional digital dental model with a 90 µm scanning layer by using micro-CT from the dental impression and presented micro-CT as an alternative for creating a dental model.

Kim *et al*.[42] compared the impression phase of crown and inlay restoration fabrication with the extraoral optical method (laboratory scanner), the intraoral optical method (intraoral scanner), and their own method (scanning the impression with micro-CT). Although different methods were used in terms of functioning, no significant difference was found between them. The proposed method has been shown to be comparable to extraoral optics and intraoral optics in conditions of dimensional accuracy. According to the outcomes of the variation map analysis, it has been shown that the recommended method has considerably less deviations not only on the tooth surface but also in the gingival tissues with respect to the intraoral optical method. They also evaluated the restorations obtained from all three methods and showed that the proposed method was comparable to existing methods in conditions of appearance and marginal fit.

In a research conducted by Hamm *et al*.,[43] the models produced from six different materials (Type IV hard plaster, cobalt-chromium-molybden, epoxy resin, polyurethane, titanium, zirconia) were evaluated. Over the course of six weeks, 3D data sets of models were produced using Micro-CT at various intervals. Cobalt-Chromium-Molybden and zirconia scans have shown the best sensitivity. While the polyurethane model does not satisfy the requirement of dimensional stability, the epoxy and type IV Hard plaster remained stable for only 10 days.

1.5. Evaluating the Effects of Occlusal Interference

Due to the early contact or lateral loads, excessive force is transferred to the teeth from prostheses and this mechanical stress may affect periodontal tissues. Excessive mechanical stress and hyperocclusion are called occlusal trauma, a type of periodontitis. Radiographic evidences in individuals with occlusal trauma, the destruction of the alveolar crest in early stages and the expansion of the interval of the periodontal ligament, then the demineralization of the alveolar bone and the loss of tooth in the following stages.[44] Recent research, has attempted to investigate alveolar bone alterations using micro-CT.[45] It was also used to evaluate the destruction of the orthodontic tooth mobility and periodontitis-related periodontal tissue damage. Micro-CT was also employed to evaluate bone patterns in segmental osteotomy research.[46]

As a result of the bone being destroyed during hyperocclusion, high mechanical stress can lead to periodontal disease. In response to hyperocclusion in rat, micro-CT was used in the study aimed at analyzing alveolar bone resorption.[47] Under anesthesia, a stainless steel wire is connected to the teeth of the rat to induce extra occlusal force loading. On the days of 0 and 7, hard tissue samples were examined with micro-CT. As a result of the research, significant bone resorption was observed on the 7th day compared to initial. This study has provided the possibility of effective examination from a prosthetic perspective of alveolar bone resorption, and the topographic images obtained have enabled hard tissue changes that cannot be detected by immunohistochemical alone.

There is a biomechanical relationship between temporomandibular joint (TMJ) and occlusion. Incorrectly created occlusion initiates degenerative responses in TMJ condyles. Aging is a factor that promotes the development of osteoarthritis. Zhang *et al* .[48] aimed to evaluate the effect of aging on degenerative remodes in TMJ condyles in response to occlusal biomechanical stimuli caused by the prosthesis used without compliance with the rules and to observe rehabilitation after prostheses were removed. In this study, the bilateral anterior cross bite model was developed to 84 female rat groups and TME 3, 7 and 11 was examined in weeks. Prostheses made with bilateral anterior cross bite model were made for 7 weeks and evaluations were made 4 weeks after the prosthesis were removed. TMJ changes were examined by micro-CT, histomorphology, immunohistochemistry and immunofluorescent painting experiments. The results have shown that bilateral anterior cross bite model causes more severe osteoarthritis-like TMJ lesions in older groups. The elimination of the bilateral anterior cross bite model has reduced the degenerative changes in the condylar cartilage and subcondral bone. The effect of healing has been found to be more pronounced especially in young animals.

1.6. Evaluation of the volumetric change in teeth due to dental post application

It is very difficult to decide on the treatment when post application is required. The posts are used to protect the remaining tissues when a large part of the tooth is lost. Access cavity and post socket preparation are processes that cause great loss of the hard tissue structure during root canal treatment. It is crucial to quantify the quantity of dentin eroded at each step of the root canal process and after the restoration to determine how the destruction of dental tissue brought on by restorative processes and root canal treatment might damage the tooth. During root channel instrumentation, high-resolution micro-CT is frequently utilized to assess the 3D volumes and geometries of canals.[49] In a study, in which the micro-CT method was preferred to examine the volume changes occurring in the dental hard tissue after endodontic procedures and it was found that the preparation of the post slot for casting post causes more dental tissue loss than fiber post socket preparation, it was founded the post socket preparation for the cast post caused a greater loss of dental tissue than the fiber post socket preparation.[50]

Micro-CT was preferred as the examination method in the study, which planned to impartially compute the volumetrical alteration of endodontically treated and post-applied teeth before and after removing the prefabricated post, and to compare the dentin volume between the samples by evaluating the alteration in tooth volume.[51] Stainless steel Parapost and glass fiber reinforced composite post samples are classified into two groups based on the post system being utilized. Half of the posts for each group were cemented with glass ionomer cement and the other half are Dual-Cure resin cement. Compared to other posts and cement combinations, the climped parallel-edged stainless steel posts with glass ionomer cement were extracted by using ultrasonic vibration method and caused the maximum loss of tooth root structure.

Chang *et al*.[52] used micro-CT, finite element analysis (FEA) and *in vitro* fatigue analysis in their study to understand the mechanism of the early dissolution of the luting cement layer occurring in the apical and peri-apical regions of fiber posts in an endodontically treated premolar tooth. The six mandibular premolars with canal treatment were examined with micro-CT prior to and during the fatigue test and various materials (dentin, bonding cement and gap) were defined to assess the volume/position of the gap. Oblique loads were applied to assess the mechanical behavior of the cement layer and fatigue tests were performed that simulate one-year chewing to compare it with the results of FEA. Most of the gaps occurred in the apical one-third of the fiber post, these gaps caused the fiber post to be released and created a stress concentration on the gap limit. In the FEA, it was found that fatigue life has decreased in experimental tests with increasing stress value/micro motion.

In the study of Soares *et al*. [53], which aimed to evaluate the size of the spaces among root dentin and titanium or glass fiber post after cementation with self-adhesive resin cement, the canal, cement and post parameters and surface spaces were measured along the cervical region of the tooth. In self-adhesive cements, the presence of interfacial gaps along the root canal was observed, which was not related to the amount of cement in the canal. There is no important difference among samples containing glass fiber or titanium, and both post kinds have a faultless interface with decimals. They reported that micro-CT is an excellent procedure to examine root canal restorations of hydrated specimens in 3D.

1.7. Evaluation of changes in the implant-abutment connection

Nowadays, dental implants are preferred because they reclaim the function and aesthetics of failure teeth and improve the quality. Two-piece titanium dental implants have been effectively employed in dental professionals for many years.[54] They need to resist the dynamic forces in the oral cavity[55] and the mors-angle (tapered) implant-abutment connections have been shown to be more durable to fatigue against mechanic forces.[56] In addition to technical failures such as chipping or fracture, screw or abutment loosening in implant restorations, implant fractures have been documented in up to 30-41% in 5 years.[57] In addition to technical complications, the prevalence of periimplant mucositis and periimplantitis (43% and 22% respectively) emerges from various biological complications.[58] Although the etiopathogenesis of periimplant diseases has not yet been entirely known, the presence of titanium ions and nanoparticles in the mucosa of periimplantitis have been shown.[59] The micro movement during the loading was defined, but the results were rarely investigated in zirconia abutments.[60] It has been proven that the cyclical loading of zirconia abutments in titanium implants caused the abrasion of titanium implant in butt-joint and conical implant-abutment interfaces.[61]

Blum *et al*.[62] aimed to evaluate the micro gap formation and corrosion pattern during cyclic loading of two-piece dental implants belonging to different systems. Several dental implant systems with various conical implant-abutment interfaces were examined utilizing first synchrotron X-ray high-resolution radiography (SRX micro-CT) and scanning electron microscopy (SEM). The implant-abutment mechanisms were then exposed to cyclic force. Microspaces were assessed after several cycles with SRX micro-CT. The corrosion mechanisms of the implant-abutment connection also characterized by using SEM after specific cycles. As a result of the study, all implants showed a micro gap among the implant and abutment before loading, and this range increased following loading. Regardless of the interface design, corrosion have been observed for all implants tested. The wear pattern is mostly in the form of adhesive corrosion and friction.

Rezende *et al*.[63] purposed to evaluate early loading in various implant platform geometries (external hexagon and morse tapered implant) using micro-CT. Abutment screws were scanned with micro-CT to create digital models. The abutments were torqued to 20 Ncm on the implant and the combination consisting of implant, abutment screw and abutment was transported to the micro-CT scanner and digital sections were obtained from the samples. These cross-sections allowed measurements of screw lengths after torque usage and based on screw elongation. Early loading levels were computed using the Hooke's Law. The extraction torques each sample was saved. To assess the accuracy of the micro-CT method, three rods of known lengths were scanned, and the length of their digital model was assessed and compared to the actual lengths. There was no difference among the groups in terms of early loading values, but the external hexagon group showed higher extraction torque values. The micro-CT method indicated a variation of 0.053% and repeatability deviated from 0.23% to 0.28%. It has been stated that the micro-CT method can be used for early loading calculations.

In a study evaluating micro gap in the screw pitch connection of a two-piece dental implant,[64] the implants were combined with 25 degrees angled abutments and micro-CT was utilized to evaluate the screw pitch engagement intervals under various mechanical conditions. The average range in the unloaded sample, is 2.9 ± 0.9 µm. the average space difference during the cyclic compressive loading was showed insignificant impact for cyclic loading. At 200 N, the micro gap size did not increase under the static compression load, but at 400 N, a considerable increase was observed. The mean micro gap significantly increased in the direction of the force application while significantly decreasing on the opposite side.

Bagegni *et al*.[65] evaluated the impact of dynamic loading on the micro gap of the implant-abutment connection when various superstructure heights are selected. 48 dental implants divided two groups (butt-joint and internal-chronic connection) each containing 24 implants, and also according to the height of the superstructure they were further divided into the subgroup. All samples were exposed to a cyclic load on a chewing simulator with a 98 N force for the 5 × 10^6 chewing cycle. The micro gap in the implant-abutment connection was examined before and after loading utilizing micro-CT and light microscope. Regardless of the height of crowns, the micro gap between abutment and implant has significantly decreased following loading in both butt-joint and internal-chronic connections.

Bergamo *et al*.[66] evaluated the effect of aging on the adaptation of zirconia abutments in the implant-abutment connection using two different methods on the and aimed to predict the survival possibility of anterior crowns supported by straight and angled abutments. Abutments were randomly divided into three experimental groups according to their laboratory aging state control, autoclave aging and hydrothermal reactor aging. Implant-abutment mismatch was identified in straight abutments with micro-CT employing the silicone replica method. For fatigue testing, the abutments were torqued to the implants and attached to standard zirconia crowns. As a result, hydrothermal aging significantly affected mismatch in addition to the possibility of surviving of zirconia abutments at greater loadings.

1.8. Biomechanical evaluation using finite element analysis

Recently, FEA is a common technique used to analyze physical events in the field of engineering and biomechanical. The use in dental research is also popular. Micro-CT scanner can be used to create a more accurate and very sensitive finite element model of smaller components such as teeth, dental implants, and dental restorations. After the micro-CT scan of a tooth, it is feasible to divide enamel, dentin and pulp into different area according to the pixel level rates or mineral volume. Following the preparation and restoration of cavity, various material characteristics are given together with the required limit conditions to mimic stress and strain variation. In a study in which a 3D finite element model of the premolar tooth was created using micro-CT and the restoration of tubercles with composite resin was simulated; it was shown that the stress models were 3D and the stress concentration levels were observed on the surface where the load was placed and near the dentin-composite bond formation.[67] In another study using micro-CT, 3D FEA was formed for dental restorative procedures and simulated various cavity designs (MO/MOD and endocrown preparation) and different restorations (feldspathic porcelain and composite resin). The findings demonstrated that the micro-CT method can produce the elaborated 3D finite element model of the teeth and simulate the effect of various treatments on the distribution of stress.[68]

In a study carried out to make FEA from 3D images obtained from micro-CT scanner and two model dental crowns and three-unit fixed partial prosthesis, tensile stresses in crowns are concentrated on the inner surface of the core, close to the implemented load.[69] For the 3-unit partial prosthesis model, the maximum tensile stresses were located in the substructure, in the cervical region of the connectors and pontics. In this study, micro-CT imaging and Mimics software were combined, emphasizing the importance of 3D models of dental crowns and 3-unit fixed partial prosthesis a design instrument in dental research. It has been stated that the 3D FEA method is an significant instrumenting estimating the stress concentration by encouraging in the structural design of dental restorations.

Micro-CT data was used in a study[70] aiming to evaluate the micro-strain and dislocation caused by dental implant restorations loaded at various levels of osseointegration utilizing FEA. Three different directions of implant loading and two levels of osseointegration were considered in the stress-strain analysis of the bone-implant combination. Bone segments are based utilizing two methods (mechanostatic strain and yield strain). The findings of this study demonstrated that when there is only partial osseointegration and when the implant is loaded by buccolingual stresses, the bone around dental implants is severely stressed. High stresses are placed on the implants in these circumstances. A significant difference in the displacements of partly and fully osseointegrated implants was discovered. Partial osseointegration has been mentioned as a possible danger for implant survival.

In a study aimed to appraise the effect of three different dental implant collar configurations under combined compressive/shear force utilizing FEA, three different models, 0°, 10° and 20°, were created with different implant collar configurations and the implant collar was at the crest level or 2 mm below positioned in D2 quality bone.[71] The maximum strain levels in both cortical and trabecular tissue at the peri-implant bone interface were isolated and evaluated. As a result of the study, all implant models distributed the load at the bone-implant interface with an identical strain model between the models. In contrast, variations were seen in the cervical region, where models with implant collar shapes of 10° and 20° had lower strain magnitudes than the model with the straight configuration. When implants are inserted at the levels of the crestal bone, these values are much lower. No difference was observed in strain values in the apical area. Implant collar configuration affected the strain distribution and amplitude in cortical bone and cancellous bone tissues. To decrease the strain levels in the bone and enhance the load distribution, it has been suggested to prefer 10° and 20° neck configurations instead of flat implant platforms.

1.9. Maxillofacial prosthesis applications

Tissue engineering is a multidisciplinary science that integrates the principles of biology and engineering, providing a specific treatment by producing bioartificial organs in the laboratory and then transplanting them into humans. Tissue engineering is also related to maxillofacial prosthetic applications. Hard and soft tissue deformities, which are secondary consequences of trauma, congenital malformation, and acquired disorders, are an important medical concern.[72] Designs with the developing technology in tissue engineering; it plays an important part in tissue regeneration by maintaining tissue volume, offering temporary mechanical capabilities and biofactors.[73] Micro-CT has been used in tissue engineering studies in last years, and 3D data from samples provide more accurate data than complementary 2D methods.

The pore numbers of maxillofacial silicone elastomer combined with two distinct methods and its impact on color repeatability and stability following two different aging procedures were investigated in a research was used micro-CT.[74] 64 disc-shaped silicone elastomer samples were prepared with two methods as manual mixing and mechanical mixing under vacuum. The pore numbers, volumes and percentages were measured using micro-CT and then aging processes were applied. Color change was observed at the beginning and finish of conditioning. Mechanical mixing under vacuum decreased the pore numbers and percentages of the silicone elastomer compared to manual mixing. The pore properties of the silicone elastomer affected the color stability.

Artopoulou *et al*.[75] aimed to investigate the microleakage patterns occurring at the interface of two maxillofacial silicone elastomeric with pure titanium when three different primers were used, and to appraise the porosity of the two tested elastomers. The percent degree of linear leakage across the bonded interface was measured by light microscopy. The percentage of void volume fraction was evaluated by micro-CT scanning. Variations in mechanical characteristics, chemical combination, and adjustments during the use of maxillofacial silicone elastomeric have been shown to alter the linear microleakage and porosity of the silicone elastomeric along the pure titanium-silicone elastomer bonding interface.

Conclusions

Micro-CT method has been proven to be available in the field of prosthetics as well as in many dental studies. The use of micro-CT is increasing day by day, especially in *in vitro* studies. It has become an important part of many academic and industrial research laboratories. Especially with the developments in digital dentistry, it is considered that micro-CT systems will be used as an important evaluation tool in research in prosthetic dentistry, which includes new materials each passing day, and maybe it can shed light on original studies.

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