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Chapter 8

Summary and conclusions

The need for proper validation and verification methodology for CAD/CAM systems is imminent. CAD/CAM systems existing of an optical impression system, design software and a fabrication machine have to perform to a certain level, whereby manufacturers need to prove the effectiveness of the system as a whole. This PhD study is dedicated to the evaluation of some selected aspects in optical and X-ray scanning and planning, design and production of restorations in computerized dentistry, which has seen a dramatic development during the past 10 years. Scanning technology developments resulted in the introduction of more than half a dozen new cone beam CT (CBCT) and intraoral scanners in the dental market. Although intraoral scanning was originally meant for the chair-side production of restorations in one appointment, we can recently see a trend that data from intraoral scanning are more and more used for off-chair production in the dental laboratory or industrial production centers. Although we evaluated the accuracy of two laboratory scanners, the same methodology applies for chair-side intraoral scanners, which are basically miniaturizations of table top scanners. Also the increased use of CBCT scanners in implant planning for guided implantation can be seen as major trend in computerized dentistry, although the price tag remains a hurdle for the average practice. The introduction of direct milling zirconia ceramics in the green form, marked the start of an explosive growth of CAD/CAM-fabrication of fixed partial dentures (FPDs) and implant abutments in the past 10 years. With the advent of tooth-colored, relatively translucent, zirconia a new high-strength material became available as a supporting structure and as a backing for esthetic veneering by dental porcelain. The high-strength zirconia, shaded as a dentin, also opened new perspectives toward digital veneering with a translucent glassceramic layer, designed and produced in functional contact with the opposing and adjacent teeth. Although we developed in 1990 the CICERO (*Computer Integrated Ceramic Restorations*) system as the first digital veneering application based on aluminiumoxid technology, in 2000, the introduction of the highly promising zirconia as a substructure material, superseded alumina as a substructure material. During development, CICERO was focused on the final product, with the highest priority for aesthetics and function. The goal was: "The development of a CAD/CAM system that allows the technician to achieve a quality level that equals to or exceeds his daily work quality". In the CYRTINA system, zirconia substructures were used. The PRIMERO (*Process for Reversed Integrated Manufacturing of Esthetic Restorations*) process, whereby with “Reversed Design” the full anatomic contour of the restoration is designed into functional contact relations first, followed by the design of the substructure. Digital veneering can standardize the manufacturing process at reduced processing times and lower costs, while simultaneously increase process predictability and product quality by improved structural integrity. We evaluated the effect of five different substructure designs on the breakstrength of a maxillary incisal crown.

Accuracy of Dental Scanners

Especially when dental surface digitization devices are used as open, stand-alone applications in dental outsourcing, a reliable standard test for comparison between is necessary. A proposed test method to be used to quantify “digitizing quality” was evaluated with respect to accuracy and reproducibility of two dental surface digitization devices. Comparability of the characteristics should become ensured. Two laser light section scanners: “DentaScope II” (3D Alliance GmbH, Germany)[D] and “D200” (3Shape A/S, Copenhagen, Denmark) [S] were evaluated by means of the “Sphere Test”, that involved repeated measurements of a precision ball (radius: 6.00 mm) according to a pre-defined protocol. The surface information was received as unmatched, overlapping point clouds and statistically processed with a the CYRTINA software package (Oratio B.V., Hoorn, The Netherlands). The standard deviation of all points as well as a measure for undercutting the equator were determined. The standard deviation for the radius for D and S were 7.7 (± 0.8) and 13.7 (± 1.0) µm respectively. The equator undercut elevations were -2.0^{o} and -0.25^{o} for scanner D and S respectively. Scanner D had a significantly higher accuracy than S, corresponding with the smaller pixel distance of the sensor. Both devices show adequate accuracy and reproducibility and have an adequate ability to detect the equator. *Relevance:* The test method showed its suitability to validate accuracyis of dental scanners and was adopted by the workgroup ISO/TC 106/SC /WG 11 CAD/CAM Systems as part of a draft ISO standard ISO/CD 12836 Dentistry — Test methods for digitizing devices used in CAD/CAM systems (2010-06-10).

Approach for validating the influence of laboratory simulation of implant placement

New digital techniques can be used to improve localization and targeting of implant placement and reduce the inherent invasiveness of surgery**.** However, further studies are needed for these techniques before they can widely accepted by implantologists. A few validation studies about the difference in accuracy between implant placement by manual drilling without any computer planning and guidance and implant placement by drilling with computer planning and a drill guide had been conducted. The aim of this study was to compare the orientation differences between planned and placed implants by manual drilling and by drilling with the help of computer planning and guidance with the CADDIMA system (Oratio B.V., Hoorn-NL), respectively. A partial dentate patients’ model was used for the study. Between the 44 and 46 a diastema was present. Two impressions of silicones (a maxilla and a mandible) were made, where after twenty-six gypsum casts (one maxilla and twenty-five mandibles) were produced. All the mandible gypsum casts were divided at random into three groups: group T, group A and group B. Group T contained five casts which were used for training. Group A and B had both ten casts. Drilling of the casts in group A was with a drill guide. Group B was the control group and the casts were manual drilled. The drill guide was made during the planning phase in which a scannographic guide with three glass balls as reference markers, a CT-scan and an optical laserscan were used. A special drill guide was produced for the pilot drill (diameter 2.0 mm), because of the big difference of diameter between that drill and the rest, namely two intermediate drills (diameter 3.6mm and 3.8 mm) and one final drill (diameter 4.0 mm). Also a registration bite was made, so that the occlusion was taken in consideration during the planning. Twenty implants with a length of 10 mm and a diameter of 4.2 mm were placed in the twenty drilled holes of group A and B. The position and direction of the placed implants in the casts were optically scanned by the optical laser scan. Difference between planned and placed implants was determined by matching. Two variables were calculated: 'XY' and 'Angle'. The XY was defined as the distance between the planned and placed implant in a two-dimensional geometry. The Angle was defined as the direction of the placed implant as reference to the three glass balls. The mean XY of group A was 0.198 mm (± 0.0950). Group B had a higher mean XY, namely 1.20 mm (± 0.681). The difference of XY between group A and B was statistically significant ($p < 0.05$). Also the difference of Angle between group A and B was statistically significant ($p < 0.05$). Group A had a mean Angle of 2.45° (± 1.55), whereas the mean Angle of group B was 7.05° (± 3.92). According to Sarment et al. (2003) surgical guidance for implant placement relieves the clinician from multiple perioperative decisions. He scanned edentulous mandibles using cone beam CT-scanner with high isotropic spatial resolution, planning five implants on each side of the jaw. With respect to measurement of the angle formed between the planned implant and the actual implant preparation, the standard technique allowed for an accuracy of 8° (± 4.5) and the test method achieved an accuracy of 4.5° (± 2). This difference was statistically significant. Di Giacomo et. al. (2005) conducted a test in which six surgical guides were used in four patients (age from 23 to 65 years old). Twenty-one implants were placed with the help of a radiographic template and computer-assisted tomography. The virtual implants were placed in the resulting three-dimensional image. With the use of a stereolithographic machine three surgical guides were made. After surgery a new CT scan was taken and the images of planned and placed implants with their location and axes were compared. On average, the match between the planned and placed implant axes was within 7.25° (± 2.67); the differences in distance between the planned and placed positions at the implant shoulder were 1.45 mm ± 1.42, and 2.99 mm ± 1.77 at the implant apex. Also in our study a statically significant improvement was found in all measurements when the drill guides were used and most importantly, variations from the mean were significantly reduced in comparison with manual drilling. The significance of this study could for instance be relevant in situations when multiple parallel distant implants are placed and when the angle of accuracy was critical for obtaining a single prosthetic path of insertion. In 2010 the University of Rome investigated the accurancy of implants placed by two commercial stereolithographic templates. All patients underwent a CT post-operative and the images pre- and post-operative were compared. Four deviation parameters (i.e. global, angular, depth, and lateral deviation) were defined and calculated between the planned and the placed implants. One showed a mean global deviation of 1.46 mm (range 3.88-0.17,SD 0.68), a mean angular deviation of 5.09° (range 21.16-0.10, SD 3.69), a mean lateral deviation of 0.97mm(range 3.15-0.08, SD 0.51)and a mean depth deviation of 0.97mm (range 3.53-0.02, SD 0.70). The other showed a mean global deviation of 1.51 mm(range 3.00-0.13,SD 0.60), a mean angular deviation of 4.67° (range 15.25-0.10, SD 2.97), a mean lateral deviation of 1.19 mm (range 2.61-0.12, SD 0.63) and a mean depth deviation of 0.74mm(range 2.29-0.03,SD 0.55). These results, allows us to confirm the reliability of two methods of computer-assisted implant placement tested. Using a CT scan-based planning system the surgeon is able to select the perfect location for implant placement, taking into account important anatomic structures and using the optimal bone densities. Research has been done to select the optimal position and to compare the outcome with the planning.

Relevance: The method can be used to show the benefit of a better predictability of guided implant placement in precision and orientation in vitro as well as in-vivo.

Computer modelling of occlusal surfaces of posterior teeth by virtual articulation

Determinants of mandibular movements, like condylar inclination and incisal guidance should be considered in the fabrication of restorations in occlusion to prevent posterior excursive occlusal interferences. This study investigated differences in the occlusal morphology of the right mandibular molar resulting from high, average and low values of settings for determinants of anteroposterior and transverse mandibular movement using a virtual articulation model. The articulation functionalities of a computer integrated restorative technology by imaging and new acquisition (CYRTINA) were used as a tool to examine the potential effect of determinants of mandibular movement on occlusal molar design. High, average and low values for condylar guide inclination, incisal guide angle and intercuspal contact area (antero-posterior determinants) and laterotrusion, mandibular lateral translation and intercuspal contact area (transverse determinants) were introduced and differences in molar morphology studied. The latter was done by comparing mesiodistal and buccolingual sections of the occlusal designs. These interocclusal differences were quantified as differences in frequency of occlusal distance intervals in an interocclusal range of 1 mm, measured from the occlusal surface of the molar model. The vertical distance with which a standard crown in occlusion had to be corrected to avoid interferences, was calculated. Among all parameters, the ipsilateral and contralateral mandibular lateral translation, sagittal condylar guide inclination, the ipsilateral laterotrusion and the incisal guide angle give substantial occlusal surface corrections. The high setting for the ipsilateral mandibular lateral translation required most correction. High and low setting values of mandibular movement determinants require considerable adaptation of the occlusal surface of a crown to facilitate functional occlusion without occlusal disturbances. In a second study the application of the CYRTINA procedure was used for the fabrication of a crown in static contact. Although this design fulfils the aesthetical demands of a dental restoration in function it deranges normal functional movements. Therefore additional corrections of the occlusal surface need to be executed in order to prevent disturbances during dynamic contact movements. Two types of settings were chosen for the fabrication of these crowns: the default values mostly used in articulators and the data obtained after digital registration of the individual contact movements. The contact movement data from an electronic registration system were used to simulate jaw movements in the CYRTINA virtual articulation software. The registration apparatus is designed for use in dental practice. However for routine restorative procedures, the application of this optoelectronic device will mostly be unproportionally time consuming and may burden the patient. In pilot studies the registration procedure has been tested in patients and produced crowns without dynamic disturbances; also the contacts in centric occlusion guarantee an optimal restoration. However, in clinical trials with greater patient groups, the practical aspects should be evaluated further. The CYRTINA system till now is the first system where data files from electronic registration could be directly implemented for crown modelling and reconstruction. In this way conventional methods, where articulators are used for the construction of the occlusal design of the crowns can be omitted. Furthermore, the difficulty to visualize in 2D projections the contact situation of spatial movements of the antagonistic teeth during function and contact movements of opposing jaws in the articulator is substituted by evalution of the designs on the CAD/CAM screens. These designs may be studied in every plane or in 3D perspective. The accuracy of a CAD/CAM crown depends on accumulated deviations: the precision and reproducabilty of the scan-design-manufacturing process. In the digital surface acquisition phase most scanners have an accuracy in the range of 10-50 (average around 15) µm. The accuracy of the manufactoring process of a restoration depends on many factors and will on average be in the same range as for scanning. Interocclusal contacts in this study were therefore defined as 50 µm - intervals. The developed computer software can be used to detect changes which occur near the buccolingual transverse ridge, which are not easily detected in the 2D pictures of 3D morphology. The spatial distribution and frequency of contacts offer a tool to detect these differences objectively. In particular, the interocclusal distance calculated in the system for each of the 5 µm points of the occlusal grid designs, related to differences in buccolingual and mesiodistal sections and of the perspective image crown designs can be judged more easily after quantitative calculation of the interocclusal situation by the computer software. For the interocclusal analysis also the quantitative frequency distribution of interocclusal distances may be helpful.

Relevance: Virtual articulation is a tool to analyse the effects of relative contact movements on occlusal morphology and can give more quantitative data about changes as a result of different parameters of the craniomandibulair system.

Comparative finite element stress analysis of zirconia and titanium abutments

Finite Element models were realized without modelling the screw thread of the implant in the bone. Although the implant design might cause significant variations in stress distribution in the bone, the difference between cylindrical and screw-shaped implants is small and the influence of this simplification on the stress distribution in the implant with abutment and screw might be negligible. Some studies neglected the preload caused by tightening the abutment screw. However, the preload is influencing the stresses and deformation in the implant and as a consequence the stresses in the bone.

The highest tensile stress in the implant with abutment and screw with the internal octagon connection was in the titanium alloy and zirconia abutment 448 MPa and 506 MPa respectively. The yield strength of the titanium alloy is 789-1013 MPa and the strength of the zirconia material is 1074-1166 MPa. However, this strength is highly influenced by the surface roughness and can be reduced to almost half of this value. In the clinical situation, when the surface finish in the corner of the octagon is not perfect, the stresses in the zirconia abutment in both executions might result in failure, especially after the fatigue effect of mastication. In the implant the highest stress was 712 MPa and 787 MPa for the titanium and zirconia abutment respectively. These stresses are close to the yield strength of titanium. In the abutment screw the stresses remained well below the yield strength. In the bone the highest stress was 34 and 36 MPa for the titanium and zirconia abutment respectively. The highest stresses in the bone were in the cortical bone and are well below the strength of the bone. The highest tensile stress in the implant with abutment and screw with the external octagon connection was in the titanium alloy and zirconia abutment 278 MPa and 260 MPa respectively; these stresses are well below the strength of the material. The highest stress occurred at the inside of the abutment just above the abutment screw. The design of the abutment with external octagon shows in this respect to be better than the internal octagon design. The highest tensile stress in the implant was 1288 MPa and 1180 MPa for the titanium and zirconia abutment respectively. These stresses are just above the yield stress of the titanium alloy and might give deformation of the implant to the point where a thicker part of the implant will support more. The highest stress in the bone was in the cortical bone, 53 MPa for both abutment materials. This is below the strength of the cortical bone. However, eventual deformation of the implant might cause persistent inflammation of the tissue at the implant –abutment interface. In the abutment screw the stresses remained below the yield strength of the material. All implant-abutment combinations showed sliding of the abutment over the contact surface with the implant. This sliding caused a micro-gap. The inflammatory process might be reinforced by the "pumping effect" of the formation of this micro-gap under the bite forces. This "pumping effect" might explain the differences found by others for different designs, while micro-leakage is unavoidable among current implant systems regardless of the connection type or interface size. The highest tensile stress in the abutment screw was between 586-763 MPa for the different implant-abutment combinations. Due to the fatigue effect during mastication, these stresses might result in screw loosening.

Relevance: Finite Element Analysis has proven to be an excellent tools to predict catastrophic stresses in ceramic implant abutments and prevent the chance for failure by an improved design.

Effect of design parameters on the failure load of PRIMERO crowns

The recommendations concerning tooth preparation design, dimensions, and shape of the zirconia core are identical for metal-ceramic crowns veneered with porcelain. The approach for the new digital PRIMERO production method of veneering was to produce identical restorations concerning dimension and core design. In all five groups, the cores were accomplished as if they were intended for clinical use. The veneer application and milling were performed according to a proprietary method, with appropriate dimensions and identical for all five groups. Cementations were made according to the manufacturer's recommendations, with zinc phosphate cement on metal-dies. According to Scherrer, increasing elastic modulus of the supporting material results in increased fracture strength. The elastic modulus of the supporting die was 200 GPa, superior to that of dentin which is 12 GPa. If natural teeth were used as the supporting model, the fracture strength of the crowns might have been lower. However, natural teeth would have been destroyed during the testing at the high fracture loads. Loading conditions and cementation were identical for all groups. Ceramic structures tend to fail because of surface stress concentration, where cracks and flaws propagate by slow crack growth leading to the catastrophic failure. In all-ceramic systems, the flaw population (size, number and distribution) can be related to the material, or be affected by the fabrication process. Thus, it might be expected that the heat pressing introduces fewer flaws than layering, resulting in better strength properties, as it is a more controlled procedure. By comparison, the layering technique is more sensitive and subject to variability due to the firing procedures. It is reasonable that the failure mode of zirconia-based all-ceramic restorations veneered with a relatively weak porcelain – assuming a good bond – tends more to cohesive chipping of the porcelain. Thus, the relatively weak veneering porcelain (90 MPa) of the specimens led to cohesive fractures, where a thin porcelain layer still remained on the zirconia coping. This type of failure indicates the good interfacial bond between the core and the veneer material that is critical for the success of these composite structures. The fracture strength of specimens with a shoulder of veneering porcelain was significantly lower than that of the other groups tested. The main reason is probably due to the non-supporting porcelain shoulder, initiating a crack. The number of total fractures also expresses the stability of the zirconia-based crowns. Fifteen of the 25 specimens failed catastrophically at a very high fracture load. Second the CAD/CAM process uses high quality material with a minimum of flaws compared to the manual procedures of veneering. The fact that ten cohesive fractures were observed also indicates that a good interfacial bond is achieved using the PRIMERO technique. Catastrophic failure as a result of contact loading has made it difficult to identify whether cone cracking or subsurface damage was responsible. It is supposed that both processes may occur at the failure site as reported by previous studies. All groups evaluated showed greater fracture loads than most available literature and exceeded the maximum chewing forces. However, clinical failure of zirconia-based restorations was reported. It is supposed that fatigue has a major effect on the mechanical stability and explains the high values compared to similar studies, such as fatigue, not taken into account in this study and. The die material, as mentioned above, has a significant influence and increased the fracture load in this study. Similar fracture loads have been reported with titanium abutments. The diameter of the loading piston can also influence the fracture strength of all-ceramic restorations. In this study used a jig was used with a large contact area than comparable studies to ensure an optimal transfer of the load onto the specimen. Increasing the loading angle can lead to lower fracture strength. The standard deviation of up to 36% was in the same range or higher compared to similar studies. This can be explained by the design of the specimens as they were designed as crowns for clinical use in this study. Other studies reporting lower standard deviations used more simplified shapes of the occlusal surface.

Relevance: The simple crown break test can give information on the relative strength in different designs and so generate guidelines for the design of restaurations.