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Measurement of dental crown wear —*In vitro* study

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The purpose of the study was to test new method for *in vitro* evaluation of dental material wear with 3D digitization procedure. Thirty dental crowns, made of polyetheretherketone and veneered with composite material, were subjected to wear test. The crown surface was digitized using coordinate measuring machine before and after the performed wear test. Mesh 3D models were reconstructed and average and maximum depth of lost material and volume loss was calculated (GOM Inspect 2016 software). Mean average depth value amounted 12±7 µm, maximum depth value was 42 µm, while mean volume loss was 0.0024 mm^3. The smallest measured values were 4 µm for depth value and 0.0003 mm^3 for volume loss. Coefficient of variation was very high for all tested parameters (>50%) as a result of data inconsistency. Within the limitations of applied methodology, the possibility of using coordinate measuring machine in measurement of dental material wear was confirmed.

Keywords: Material wear, 3D digitizing, Extraoral scanning, Coordinate measuring machine, Scanning accuracy

INTRODUCTION

Wear resistance is one of the characteristics needed for a dental material to be accepted in everyday practice. With upgrading biomechanical characteristics and longevity of dental materials, improved measurement techniques are needed in order to evaluate their behavior during functional loading. A variety of methods for investigating wear of dental materials includes the usage of intra and extraoral scanners and wear machines[1,2)]. So far, many clinical studies have been conducted but they are time consuming and it is difficult to quantify amount of tooth/dental material wear. The lack of control over environmental factors and recall failure limit contribution of *in vivo* studies to scientific evidence[1,3,4-8)]. *In vitro* studies have been shown as valuable in providing basic information about mechanical characteristic of restorative materials[1,3,4,7,8)]. Although laboratory environment cannot exactly simulate conditions in the oral cavity, *in vitro* studies can be useful to predict the longevity of dental materials[1,9)]. However, there is no unique guidance for examining surface of dental materials[1,10)]. Regarding this, there is the need for scientific protocol for evaluating wear of dental materials in three-dimensions.

Different types of three-dimensional (3D) scanners provide reconstruction of an object in a virtual environment. The main demand for any type of scanner is its accuracy which consists of exactness- deviation of the scanned object from its real geometry, and precision-deviation between repeated scans (ISO 5725-1)[10,11,12)]. Latest generation of coordinate measuring machines (CMMs) are complex mechatronic devices that have reached an acceptable level of accuracy[10)], especially when applied with advanced contact, *i.e.* tactile, measuring probes. New methods of CMM inspection use styli, *i.e.* measuring tips that travel across the surface recording points position at specified step intervals which is why they are more accurate and more often faster[13,14)]. Although various optical measuring sensors have been increasingly applied in different areas, mostly because of their high acquisition speed, they still have not reached the accuracy of the new generation of tactile measuring probes. This is the reason why tactile sensors could be in advantage in cases where specific measurement, such as wear measurement of dental materials, is required.

This research was focused on methodology for dental material wear analysis. The advanced CMM Contura G2 (Carl Zeiss, Oberkochen, Germany) was applied for measurement due to its high scanning accuracy. The other reason for selecting CMM Contura G2 was inability to scan highly reflective and shiny surface of the dental crown with optical 3D digitizing methods. New biomaterials, that meet increased expectations from composite materials, are being constantly developed and this field needs to be further investigated. For testing material was chosen polyetheretherketone BioHPP (Bredent, Senden, Germany), covered with with Crea.lign composite material (Visio.lign veneering system, Bredent). A modified protocol for surface scanning of the crown was used before and after thermal and mechanical loading. The tested hypothesis was that CMM is able to detect and measure changes in surface appearance of dental crowns after performed wear test.

Color figures can be viewed in the online issue, which is available at J-STAGE.

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MATERIALS AND METHODS

Preparation of samples

Study group consisted of thirty dental crowns cemented on metal abutment teeth. Producing of model abutment tooth included: crown preparation of one extracted premolar (margin design-1.2 mm circumferential rounded chamfer, occlusal reduction of 1.5 mm and a total convergence angle of 6º) and positioning on square wax stand. Making the mold from the additive silicone (Elite® HD+, Zhermac, Rovigo, Italy) enabled the production of thirty wax models which were then used to obtain models of Co-Cr alloy (Remanium® 2000+, Dentaurum, Ispringen, Germany) with conventional casting method. The sample crowns with reduced premolar occlusal morphology (Fig. 1) were made of polyetheretherketone (BioHPP, Bredent), a partially crystalline thermoplastic resin reinforced with ceramic particles, using vacuum press system "for 2 press". Acorrding to the manufacturer recommendation, polyetheretherketone substructures were veneered with nanohybrid Crea.lign composite material (Visio.lign veneering system, Bredent). Inner side of the crowns was blasted with aluminium oxide (110 µm) at 2 to 3 bar blasting pressure and moisturized with light-hardened Visio.link PMMA & Composite Primer (Bredent) and then polymerized 90 s with a light polymerisation device (M+W Superlite power pen, M+W Dental Müller und Weygandt, Büdingen, Germany) in accordance with the "visio.link" processing instructions. The restorations were cemented on metal alloy models using a light- and dual-curing luting composite (Variolink® Esthetic LC, Ivoclar Vivadent, Amherst, NY, USA) following the manufacturer's recommendation.

Surfaces of dental crowns were scanned before and after performed wear test. The scanning of all samples was carried out on the CMM by the same operator, who used the same approach for all thirty samples. Scanning protocol on CMM was adjusted in order to evaluate effects of the performed wear test.

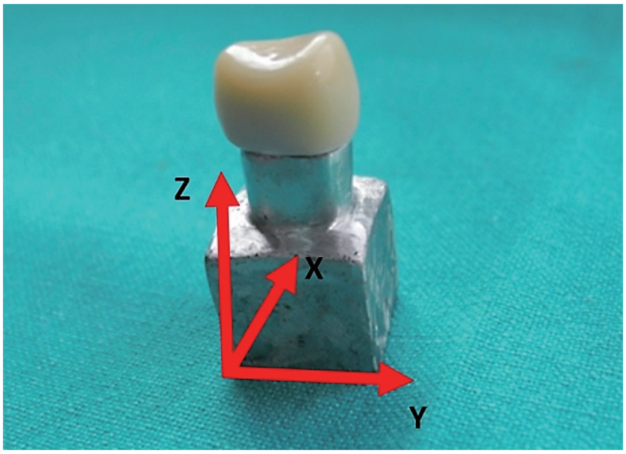

Fig. 1 Dental crown sample with reduced occlusal morphology of premolar.

The pre wear scanning of dental crowns

All crown samples were 3D digitized on a CMM Carl Zeiss, Contura G2 (Carl Zeiss), equipped with a contact probe. Maximum permissible error for size measurement (MPEE) of this CMM is 1.9+L/330 µm. Before 3D digitizing procedure the CMM was calibrated and a measurement stylus with synthetic ruby head of 1 mm in diameter was used for 3D digitization. All samples were positioned and placed in a clamp (Fig. 2). Since the CMM was located in a laboratory, the controllable microclimate conditions were fulfilled. After the preparation of CMM was completed, the 3D digitizing procedure could start. The coordinate system of all samples was placed in a metal base of the crowns.

The first set of samples was 3D digitized with dense gridline strategy placed on the crown surface where chewing simulator styli will have impact (occlusal surface, Fig. 3). 3D digitization using this grid strategy was performed in two axes (X and Y axis) for better

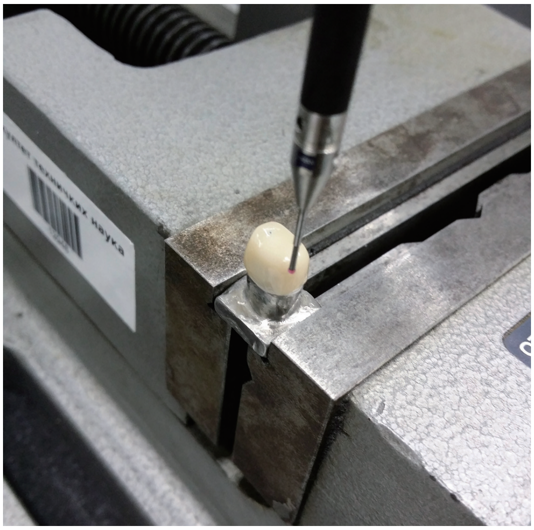

Fig. 2 Clamping of the dental crown sample.

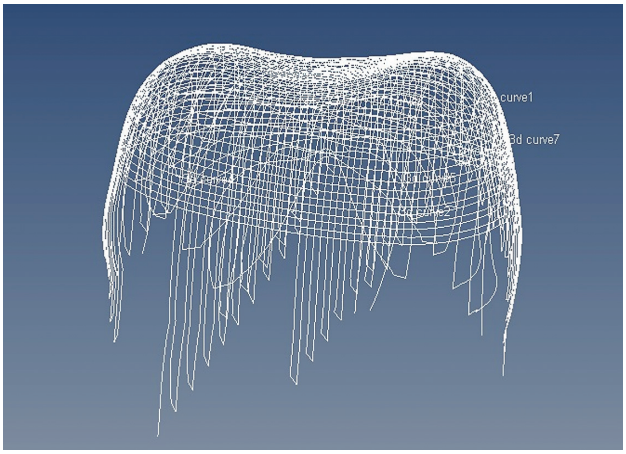

Fig. 3 Digitized point cloud shown in CALYPSO software.

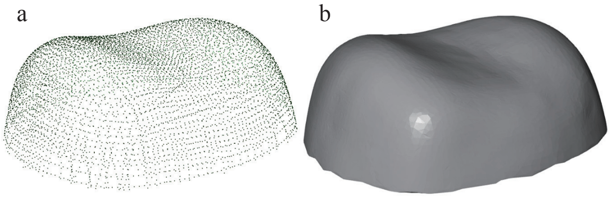

Fig. 4 a) Offset point cloud and b) polygonal 3D model of the dental crown sample no. 1.

coverage of the area that will be exposed to chewing forces. The used grid strategy parameters were 0.2 mm step (distance between two consecutive points), and 0.2 mm was the space between the grid lines. With these parameters set the total number of acquired points per one scanned sample was in a range between 9,500 and 11,000 points. In order to properly align first and second batch of samples, the outer surface of the teeth was also digitized in less detail. This enabled accurate alignment of models before and after the performed wear test. As a result, a point cloud that contained points X, Y, Z coordinates, along with their respective vectors i (X), j (Y), k (Z), was obtained. The final step was to offset the point cloud by a 0.5 mm in order to compensate radius correction of the measurement styli (which was 1 mm in diameter).

The next step involved polygonization or meshing of extracted point cloud. For all thirty samples polygonal 3D models were obtained, which were needed for analysis. The software used for this purpose was GOM Inspect 2016 (GOM, Brauschweig, Germany). The Fig. 4 shows point cloud and the corresponding polygonal 3D model.

Wear test

Wear test, which included thermal cycling and dynamical loading, was performed in order to simulate an effect of an oral environment on dental crowns. Custom made thermal cycler was specially designed for the purpose of the study (Fig. 5). On the basis of the main thermal cycling protocol, proposed by International Standards Organization (1994, ISO TR 11405), the following parameters were chosen: temperature regime- 5ºC/55ºC, the number of cycles- 3,000 and dwell time- 30 s[9].

Dinamical loading was achieved using the dual-axis chewing simulator CS-4 (SD Mechatronik, Feldkirchen-Westerham, Germany, Fig. 6). A standardized stylus, made of stainless steel, hits specimens with a 5 kg weight and a descent speed of 60 mm/s. A weight of 5 kg, comparable to 49 N of chewing force, is mounted on a bar which is driven by a computer controlled stepper motor. After the samples have been embedded in methacrylate (Technovit® 9100, Heraeus Kulzer, Hanau, Germany) in the test chambers, the chewing simulator was calibrated and the reference point (point “zero”) was defined. Before loading, the contact point between the chewing simulator styli and the dental crown was checked using a thin articulating paper (“Arti-Check®” micro-thin 40 µm, Bausch, Köln, Germany). In order to simulate a one-year chewing period, wear test was conducted with 240,000 loading cycles[3,15].

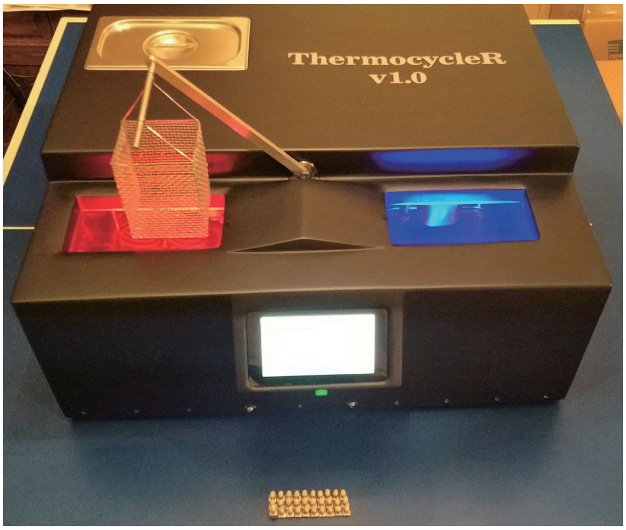

Fig. 5 Custom made thermal cycler (ThermocycleR v1.0).

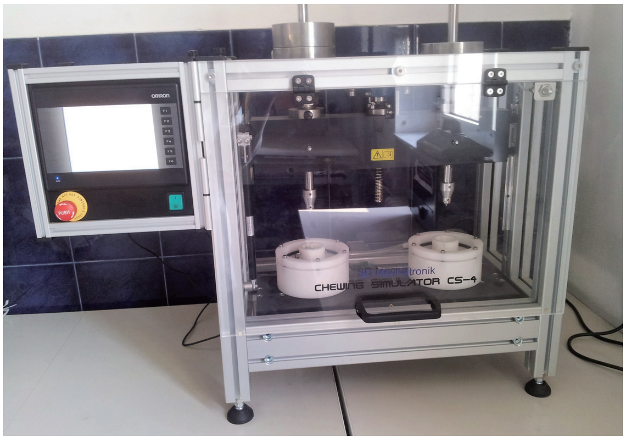

Fig. 6 Chewing simulator CS-4 (SD Mechatronik, Feldkirchen-Westerham, Germany).

Post wear scanning of dental crowns and deviation analysis

After performing wear test, the same scanning protocol on the CMM was repeated during the second scanning of dental crowns. The geometrical changes of the region, where chewing simulator styli impacted the dental crown, were analyzed using CAD inspection. This technique is based on overlapping the 3D surface models generated on bases of the results of scanning before and after the wear test. The software used for this analysis was GOM Inspect 2016 software. Within conducted geometrical analysis the first step was the overall surface evaluation. This enabled identification of the region impacted with the chewing simulator styli (Fig. 7a). Afterwards, in order to obtain detail quantification of geometrical deviations, *i.e.* wear of dental crowns, cross-section

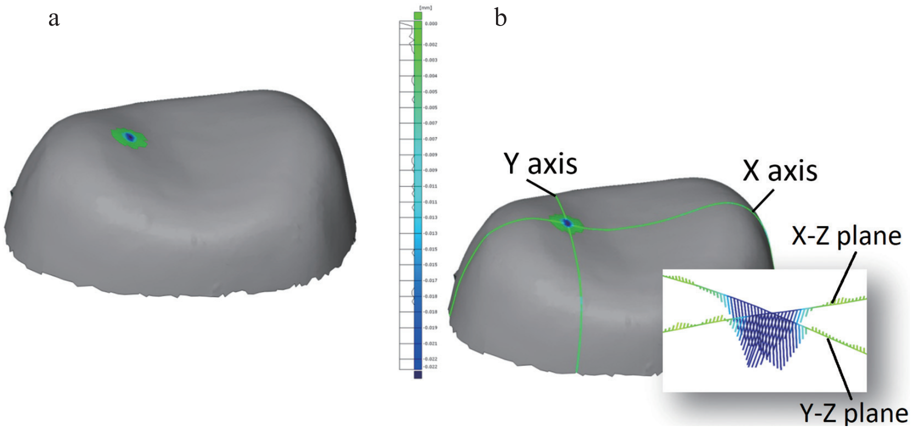

Fig. 7 a) Geometrical analysis (sample no.1) —identification of the impacted region, b) cross-section deviation analysis.

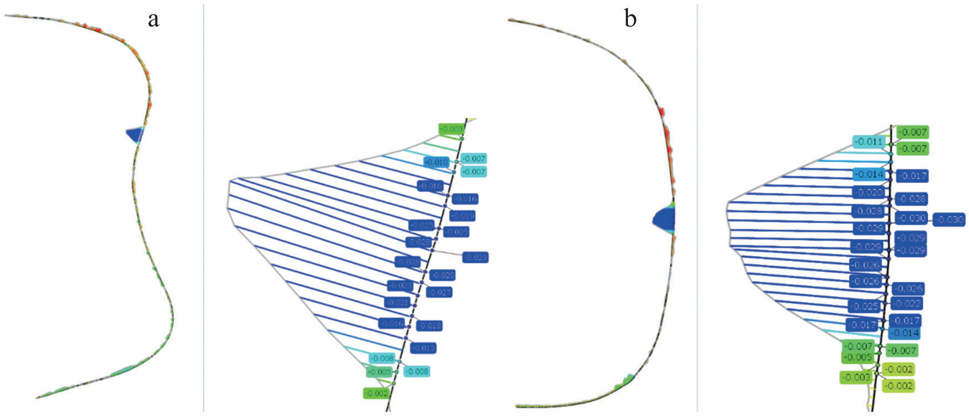

Fig. 8 Cross-sectional analysis of the created crater with quantified deviation values in X-Z (a) and Y-Z planes (b).

analysis (in X-Z and Y-Z planes) was performed (Fig. 7b). Visual representation of cross-section inspection was enhanced by changing the scale of deviation vectors by a factor of 14. On the bases of cross-sectional analysis, it was possible to obtain quantified values of deviation in each measured point acquired during 3D digitization, within the created crater (Fig. 8). This approach enabled extraction of numerical values needed for determination of average and maximum depth values.

Volume calculation of crown wear

After the cross-section analysis, the next step was to calculate the volume loss that was caused by a crown wear. The volume loss was calculated by subtracting the results of scanning before and after the wear test. The first step is the alignment of two 3D mesh models which was calculated based on Prealignment option, and final calculations were performed using Local Best-Fit method (GOM Inspect 2016 software). After this, the result obtained was the top and bottom surface of the area where the crown wear occurred. They were fused into a single 3D model in order to calculate the volume loss (Fig. 9). This process was performed for all thirty samples in order to obtain volume measurements.

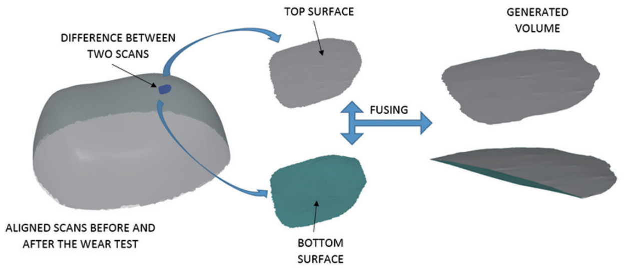

Fig. 9 Workflow of the process for obtaining volume measurement for sample no. 27.

Statistical analysis

Results are presented as mean±sd, 95% confidence interval for mean, median (min-max) and coefficient of variability. Mann Whitney test was chosen for comparing average depth values between X-Z and Y-Z plane, as well

Table 1 Description of measurements of dental materials wear

Parameters	Mean	95% CI	Median (min-max)	CV (%)
mean x-z (μm)	12±7	10–14	9 (4–28)	58.33
mean y-z (μm)	12±7	9–14	8 (4–30)	58.33
max x-z (μm)	19±10	15–23	12 (5–39)	52.63
max y-z (μm)	19±11	15–23	13 (5–42)	57.89
volume (mm^3)	0.0024±0.0155	0.0018–0.0030	0.0021 (0.0003–0.0064)	64.37

CI: confidence interval, CV: coefficient of variation, perc: percentile

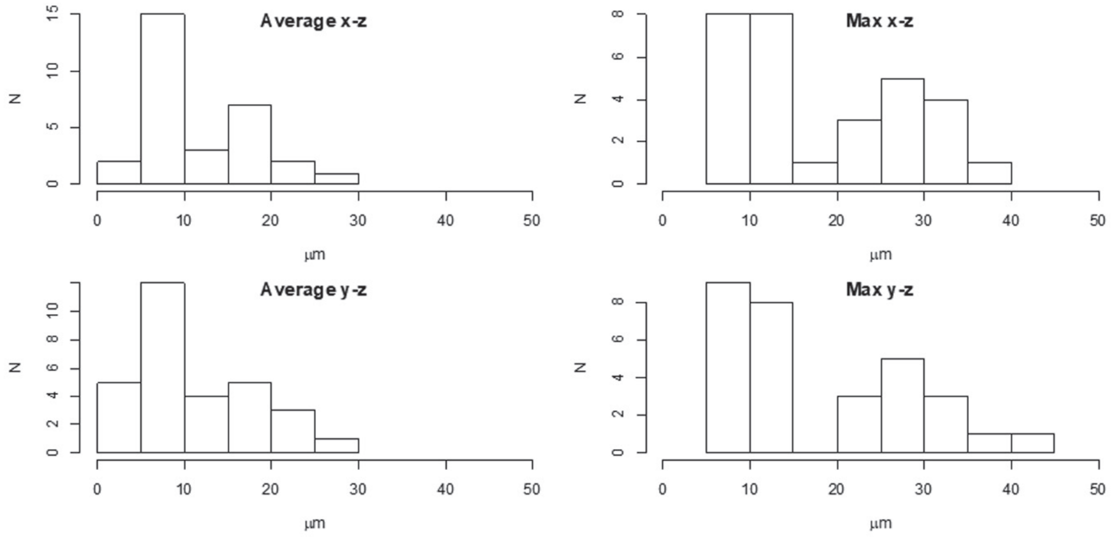

Fig. 10 Average and maximum deviation values (μm) detected in cross-sections of the craters (X-Z and Y-Z plane).

maximum depth values. Results are presented using histograms and scatterplots. Pearson correlation was used to assess significant relationship between average depth in X-Z and Y-Z planes with volume loss. All data were analyzed using R statistical software (R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Descriptive statistics of all examined variables is presented in Table 1.

No statistical significant difference was found comparing average depth values for X-Z and for Y-Z plane (p=0.766). Also, no statistical difference between maximum depth values for X-Z and for Y-Z plane was noticed (p=0.923). However, using two cross-sections instead of one helped to more precisely define the place with the greatest depth of the crater.

Distribution of average and maximum X-Z and Y-Z variables and volume loss are presented using histograms (Figs. 10 and 11).

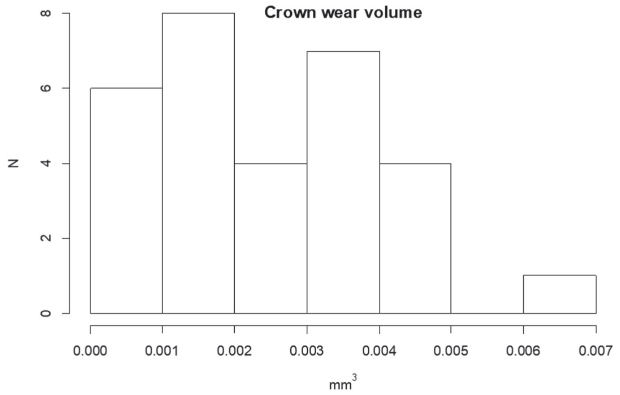

Fig. 11 Crown wear volume (mm^3).

Additionally, the correlation between the parameters average depth for X-Z plane and volume loss, as well for average depth for Y-Z plane and volume loss, was analyzed (Fig. 12). The values of obtained coefficients of correlation indicate a strong positive correlation between observed parameters.

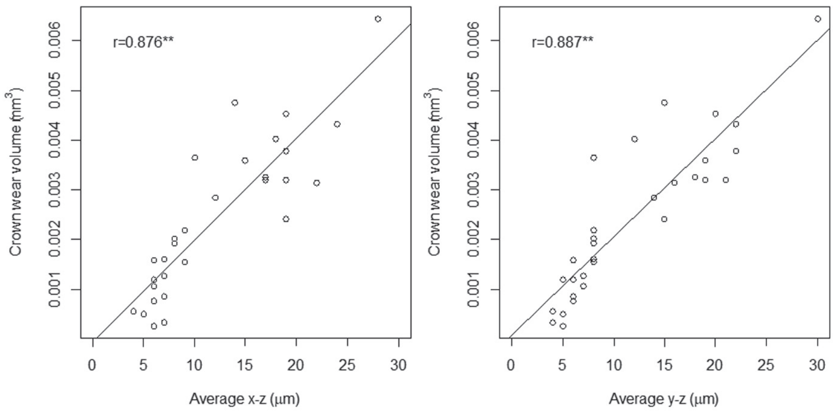

Fig. 12 Correlation between Average X-Z and Y-Z with Crown wear volume.

DISCUSSION

CMM is a measuring device for objects with complex measuring features, commonly used for geometrical measurement of mechanical parts[16-18]. The contact with the object of measurement is achieved by tactile measuring probe equipped with styli with spherical end, which registers a set of measuring points organized in a so called point cloud. Reconstruction of a virtual model allows conducting the analysis of dimensions and surface of the object[13,19]. Coordinate measuring machine that was used in the presented study Carl Zeiss, Contura G2 (Carl Zeiss) is a mid-range type CMM in combination with VAST XXT tactile measuring probe with scanning ability. Despite its application in different areas, so far CMM has not been applied for measurement of dental materials wear. Crea.lign composite material (Visio.lign veneering system, Bredent) was chosen as a test material. Compared to conventional composites for intracoronal fillings, Crea.lign composite is subjected to occlusal stress under different conditions. The fact that is used as veneering material for fixed and partial dentures, led us to examine its wear characteristics.

Recent *in vivo* or *in vitro* wear quantification methods for measuring material loss included measuring weight, height, mean height and volume loss parameters. Among them, mean height and volume loss parameters are more clinically relevant[2]. In the present study, scanning of each sample was performed in two planes (X-Z and Y-Z plane). The cross-sections that passed through the lowest point of the crater and had the maximum depth values were taken into account. After extraction of numerical values, it was confirmed that maximum depth values did not represent actual depth of created craters because of their irregular shapes. For that purpose, the average depth values (average height loss) and values of volume loss were calculated. The smallest measured values were 4 μm for both planes (minimum depth value) and 0.0003 mm^3 (minimum volume loss).

The statistical analysis revealed high values of coefficient of variation (CV>50 %) for all tested parameters. Substantial difference in the wear rate of individual samples is related to the methodology of the study *i.e.* to the shape of the samples. Even though many studies use the cylinder or disc-shape samples[4,20], in this study anatomical shape (single dental crown with reduced morphology) was chosen[21]. This geometry supposed to contribute achieving more realistic conditions that exist in the mouth, when it comes to tooth/dental material wear during function. The CMM inspection of complex occlusal surfaces is time-consuming and can be limited due to the size of the measuring probe[11,12]. The original occlusal surface scanning would last much longer but would not significantly contribute to the measurement results (it was established that wear is more likely to occur at occlusal contact areas than on contact free areas[3,6]). Therefore, the samples for this study were produced with reduced occlusal morphology. As for natural occlusion, the shape of sample crowns was not identical and had different incline of cusps. Furthermore, occlusal contacts *i.e.* place where the chewing simulator styli hit the sample, had different location (on an incline or on a flat central part of the occlusal surface). Depending on whether chewing simulator styli had contact with an incline or a flat central part of occlusal surface, lower or higher wear of material was measured. Comparing the wear result with the sample scan, it was noticed that samples with the lowest wear results had contact of the chewing simulator styli with an incline *i.e.* cusp of dental crown. Impossibility to determine a strict border between incline and flat parts of occlusal surface, made it difficult to conclude how location of occlusal contact affects the amount of materials wear. Different wear rate among flat and crown-shaped samples was also noticed in the research of Wimmer *et al.*, where flat samples showed higher material loss[21]. Differences in the anatomical shape of experimental samples or dental restorations between test persons can make a restoration more prone to occlusal wear than another restoration[3,22]. High variability of wear results was also found in the clinical researches with split-mouth design (mean CV was 53%), which pointed to the fact that the test person himself played a major role in the clinical wear performance of a material[22]. Although experimenting with geometrical shapes simplifies the wear analysis, more significance should be given to the anatomical shape of testing samples considering that low correlation between laboratory and clinical conditions has already been established[1,3,5-8,21,22].

Beside the anatomical shape of samples in this study, wear method might have an influence on material wear. A systematic review of Heintze *at al.* reveled that there can be discrepancies in wear rates of the same material using the same wear method and wear parameters (wear data differed as much as 72% from one publication to another)[3,22]. The variations may be due to material itself or the wear simulating device which may not always generate wear in a standardized and reproducible way[3,22]. In the present study, a wear test was adjusted to the objective of the study and thermal and mechanical preparation of the samples was performed separately. Guided by the conclusion of Stewardson *et al.* (2010), who estimated that 500 thermal cycles correspond to the period of nearly 2 months *in vivo*[9], the number of thermal cycles was increased from 500 to 3,000. The number of loading cycles in chewing simulator, which corresponds to the period of one year, was chosen in order to verify whether the scanner is able to detect very small changes in the surface appearance[3,15]. For the same reason, the chewing simulator was set without lateral movement because it was confirmed that lateral force application mostly led to significantly higher material loss[3,21].

Results from one wear testing method to another are hardly comparable (different sample type, different wear and scanning method)[2,22]. On the other hand, wear of different types of composite material with different indications (composites for intra-coronal restorations-direct/indirect and composites for crowns and bridges) can vary significantly[3,6,22-26]. Composite's particle size, shape and hardness, filler content, interparticle spacing, filler distribution, degree of conversion, *etc.* directly affect the material behavior[3,6,22-26]. Different data about average wear rate found in the literature are mainly result of operator variations, patient variations and the wear evaluation method[3,6,27]. Based on previous research, different values of enamel mean vertical height loss are being reported. Approximately 30 to 40 μm per year is measured in the molar region in enamel occlusal contact area, as well as 15 μm for premolars, mostly in the research of Lambrechts *et al.*[5,28-30]. In some studies enamel wear of 10 μm per year is often used as a reference[1]. American Dental Association (ADA) require that the annual wear rate of a dental restorative material does not exceed 50 μm[3,28,31,32]. For composite materials, obtained values for mean vertical height loss were usually between 20 and 40 μm per year[1]. Earlier studies confirmed that composite wear is significantly higher in larger posterior restorations compared to small and moderate-sized restorations[32]. So far, researches have usually measured wear of composite fillings which are mostly protected by surrounding hard dental tissue. It was confirmed that wear characteristics of posterior full composite crowns differ considerably from Class II composite restorations with cuspal enamel support[3]. Wear of intracoronal composite restorations is assumed to be self-limiting due to protection of surrounding enamel[3]. To our knowledge there is a limited number of researches about wear of composite crowns or crowns veneered with composite material. In research of Ekfeldt and Oilo (1990), wear of posterior full crown composite restorations was 3 to 4 times greater than wear of porcelain or metal crowns, compared to porcelain fused to metal antagonist (PFM)[32]. Depew and Sorensen (1998) presented a study with composite veneering material (Artglass, Heraeus Kluzer) where mean maximum wear depth, measured after two years, was 113 μm, with a range of 56–480 μm[32]. Similar results were obtained in 1–2 year study of three prosthodontic composites (belleGlass, Artglass, Targis) placed as crowns which was carried out by the Clinical Research Associates (1998)[32]. Different measurement results, related to volume loss of composite materials, are also being published. Acorrding to research of Heintze *et al.*, volumetric wear differed quite considerably- between 5.5 and 147×10^{-2} mm^3 on average when using flat specimens, 120,000 chewing cycles and lateral movement[33]. Lazaridou *et al.* have tested wear resistance of composite materials under similar *in vitro* conditions and reported values between 67.93 and 116.62 μm for mean vertical height loss and 0.1046–0.3738 mm^3 for mean volume loss[34]. Wimmer *et al.* conducted a complex research in which mean volume loss of experimental CAD/CAM nanohybrid composite was 118×10^6 μm^3 (with lateral movement) and 19.59×10^6 μm^3 (without lateral movement) for crown shaped samples, *i.e.* 186 $\times10^6$ μm^3 (with lateral movement) and 39.44×10^6 μm^3 (without lateral movement)[21]. In the present study mean average depth value (mean average height loss) amounted 12±7 μm for X-Z, as well for Y-Z plane and mean volume loss was 0.0024 mm^3. However, wear rate of Crea.lign composite material cannot directly be compared to previously reported studies because wear test was performed without lateral movement which reduced materials wear rate. Taking into account the specificity of the applied methodology and material indication, results of this study speak in favor of good mechanical properties of tested material. Despite the repetitive contraction/expansion stresses and mechanical load, there was no separating of the veneer material from the substructures or occurrence of cracks in the veneer material. There is still a need for clinical wear studies as wear patterns that occur in the mouth may be significantly different.

Although CMM is an instrument of great accuracy, it is necessary to know the geometry of the measurement object in order to obtain reliable results[12]. Different factors have an influence on CMM accuracy and affect the measurement results. Understanding the relationships between them is crucial for improving CMM accuracy through compensation of errors from CMM itself and from the measurement environment[18,14,35,36]. For the measurement accuracy, calibration of the probe styli is very important procedure[36]. Effective strategy for a coordinate measurement requires selection of a proper sampling area and a grid size, as well as a diameter of the styli's spherical end. Optimal sampling area should ensure the greatest probability of locating the maximum deviation at the smallest number of points[37,38]. Large number of measurement points (9,500–11,000 points per sample) and cross-section analysis of the object in two planes (X-Z and Y-Z), performed during the research, enabled a very detail analysis of the materials height and volume loss. The strong corelation between average depth values of created craters and volume loss suggests that wear measurement performed with this methodology is reliable. The tested hypothesis that CMM is able to detect and measure changes in surface appearance of tested crowns after thermal and mechanical loading was confirmed. The potential limitation of this study is measuring of dental material wear with only one type of extraoral scanner (CMM). Volumetric probing uncertainty test (P test) and volumetric length measuring uncertainty (E test) has already been recommended by ISO 10360-2 as accuracy tests for CMMs[17]. In previous studies, CMM served as a reference scanner for testing the accuracy of different lab scanners[10,39,40] or dental impressions[41]. Therefore, we consider that it is not needed to conduct control scanning of dental crowns and we restrain from further data comparison. The other limitation is the fact that each sample crown was individually made by technician. That disabled its standardization and made it difficult to conclude to what extent location of occlusal contact affects material wear rate.

Although laboratory wear methods have some limitations, they may help to predict the material wear behavior before it is tested in a clinical trial[22].

Precise, reliable and relatively simple methodology for quality control of dental materials is required, accepted from both researchers and manufacturers, in order to standardize future researches and provide inter-comparisons of their results. Methodology and the results of this study should provide useful guidelines for future studies and contribute to the improvement of the quality of dental restorations.

CONCLUSION

Coordinate measuring machine Carl Zeiss, Contura G2, Germany, which was used in the present study, has proven to be applicable for scanning smaller objects like single tooth/crown and estimation of their surface. Beside the CMM, the correct additional software is the key for accurate measuring of surface loss during the testing.

The main advantage of using CMM for wear analysis is measuring both height and volume loss of dental material.

Difference in amount of dental material wear is related to the shape of crown samples used in this study. Focus of future investigations should be on defining the right shape of samples (geometrical *versus* anatomical) as it could be one of the key factors for experimental tooth/material wear to correspond to clinical one.

Current results point to a great benefit of the reference scanner for evaluating the dimensional stability of dental material which could contribute to further investigations of new dental materials.

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CONFLICT OF INTEREST

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