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Application of Replica Technique and SEM in Accuracy Measurement of Ceramic Crowns

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The paper presents a comparative study of the measuring values of the marginal gap related to the ceramic crowns made by dental CAD/CAM system using the replica technique and SEM. The study was conducted using three experimental groups, which consisted of ceramic crowns manufactured by the Cerec CAD/CAM system. The scanning procedure was carried out using three specialized dental 3D digitization systems from the Cerec family – two types of extraoral optical scanning systems and an intraoral optical scanner. Measurements of the marginal gap were carried out using the replica technique and SEM. The comparison of aggregate values of the marginal gap using the replica technique showed a statistically significant difference between the systems. The measured values of marginal gaps of ceramic crowns using the replica technique were significantly lower compared to those measured by SEM. The results indicate that the choice of technique for measuring the accuracy of ceramic crowns influences the final results of investigation.

Keywords: Accuracy, CAD/CAM, replica technique, SEM, ceramic crown

1. INTRODUCTION

DEVELOPMENT of medical science over the last several decades is characterized by ever increasing interdisciplinarity, which is reflected in the implementation of various engineering achievements [1,2]. Dental prosthetics has always maintained close relationships with engineering disciplines, mostly relying on production engineering. Rapid development of Computer-Aided technologies, which completely transformed production engineering, also left an indelible mark on dental prosthetics. The area of dental prosthetics has introduced numerous novel technologies and methods which allow manufacture of accurate, custom-made, optimal dental restorations. During the last decade, efforts have been concentrated towards advancement of modeling and manufacture of dental restorations by introducing modern Computer-Aided equipment, state-of-the-art materials and machining technologies, as opposed to the traditional way of manual manufacture which is prone to numerous subjective errors. Among the modern Computer-Aided systems, which have found broad application in this area, the most widely used are 3D digitization systems, Computer-Aided Design and Reverse Engineering, Computer-Aided Manufacturing, Rapid Manufacturing, Rapid Prototyping, etc. The development and implementation of such technologies and systems have paved the way towards significant advancement of conventional modeling, manufacture and inspection of dental restorations [3]-[5].

The accuracy of fixed dental restorations is an important measure of their quality in addition to fracture resistance and aesthetic characteristics [6]. An excellent marginal adaptation will minimize the plaque accumulation and reduce the chance for recurrent caries and periodontal disease. There are a large number of studies that investigate and describe methods for measuring the accuracy of fixed partial dentures at the level of internal and / or marginal gap [7]-[12].

The term marginal gap cannot be described in a simple way. The definition that could be often found in the literature is that the marginal gap is the quantitative value - space (discrepancy) between the edge of the crown and the demarcation of the preparation on the tooth. A significant explanation of the term was given by Holmes, who believes that the discrepancy between the crown and the tooth is a combination of discrepancy between the edge of the crown and the tooth and error in extension of the crown edge [10]. Discrepancies between the inner surface of the crown and the tooth are defined as inner gap, while the same mismatches at the edge are labeled as marginal demarcation gap. Morphological mismatches and irregularities between the crown and the tooth, as well as their differences in marginal contours are usually the reason for the appearance of clinically unacceptable marginal gap. Results of previous investigations point out that marginal gaps below 100μm are clinically acceptable [11,13].

Different methods for measuring and evaluating the marginal gap can be found in the literature and they all have their advantages and disadvantages. Sorensen et al. proposed classification of methods into four basic categories: direct observation, cross-sectional measurement, impression techniques, and the use of an explorer with a visual examination [9].

Qualitative techniques such as impression technique and visual examination are not accurate; they are often subjective and depend on the experience of a researcher and his/her tactile sensation [14]. Application of these techniques - often used in everyday clinical practice - is less objective when the region of demarcation is located subgingivally [15]. Besides, the imprecise radiographic techniques are limited with respect to material type and its sensibility to X-rays.

Impression techniques with impression material of low viscosity (replica technique) are popular methods for evaluating marginal discrepancies between the crown and the tooth. Their application can be constrained when testing the dental device with good fitting, because there is a danger of damaging the impression material when separating the crown (dental device) from the master die and getting inaccurate results [16,17]. Some authors suggest profilometry as the method of choice for measuring the size of the marginal gap [15,18].

Scanning electron microscopy (SEM), optical stereomicroscopy and measurement of discrepancy between crown and tooth by microphotography are techniques that are often used for measuring the accuracy of fixed dental restorations [19]-[21]. Those techniques are relatively accurate and their use does not cause destruction of the sample. On the other hand, it is considered that the angle at which the object is observed affects the accuracy of the measurement. Also, sample preparation for SEM microscopy techniques (molding, cutting, and polishing) can damage the sample and reduce the accuracy of the method [22]. There are lots of methods for measuring the accuracy of fixed partial dentures among which are also the impression replica technique and SEM. However, the question is whether the choice of technique affects the results of the measurement.

The goal of this paper was to apply the replica technique and SEM to measure marginal gaps of ceramic crowns made by the Cerec CAD/CAM system, and to compare the measured values.

2. SUBJECT & METHODS

Basic steps of methodology applied in this work are shown in Fig.1. The method used for manufacturing the ceramic crowns comprises following steps: preparation, 3D digitization (scanning), modeling (Reverse Engineering and Computer-Aided Design), and manufacture (Computer-Aided Manufacturing). Accuracy measurement of ceramic crowns is conducted after the steps listed above have been completed.

The complexity of preparation depends on whether tooth scanning is performed intraorally (inside patient's oral cavity) or extraorally (outside patient's mouth cavity). In this investigation acryl teeth were used (DSP - model teeth, Nr.11 KaVo, Germany), which were set in an operating model (KaVo, basic study model, Germany).

Teeth preparation was performed according to recommendations for the Cerec CAD/CAM system, which included the rounding of demarcation shoulder by 1 mm, inclination of axial surfaces by 6°, and occlusal reduction by 1.5 mm (Fig.2). Approximately 1 to 1.5 mm of tooth substance was removed from axial surfaces [23]. Finishing of abutments was performed by fine diamond borers (Logic-Set3, NTI). Using the described methodology 8 acryl teeth were prepared and subsequently used as a master preparation (Fig.3).

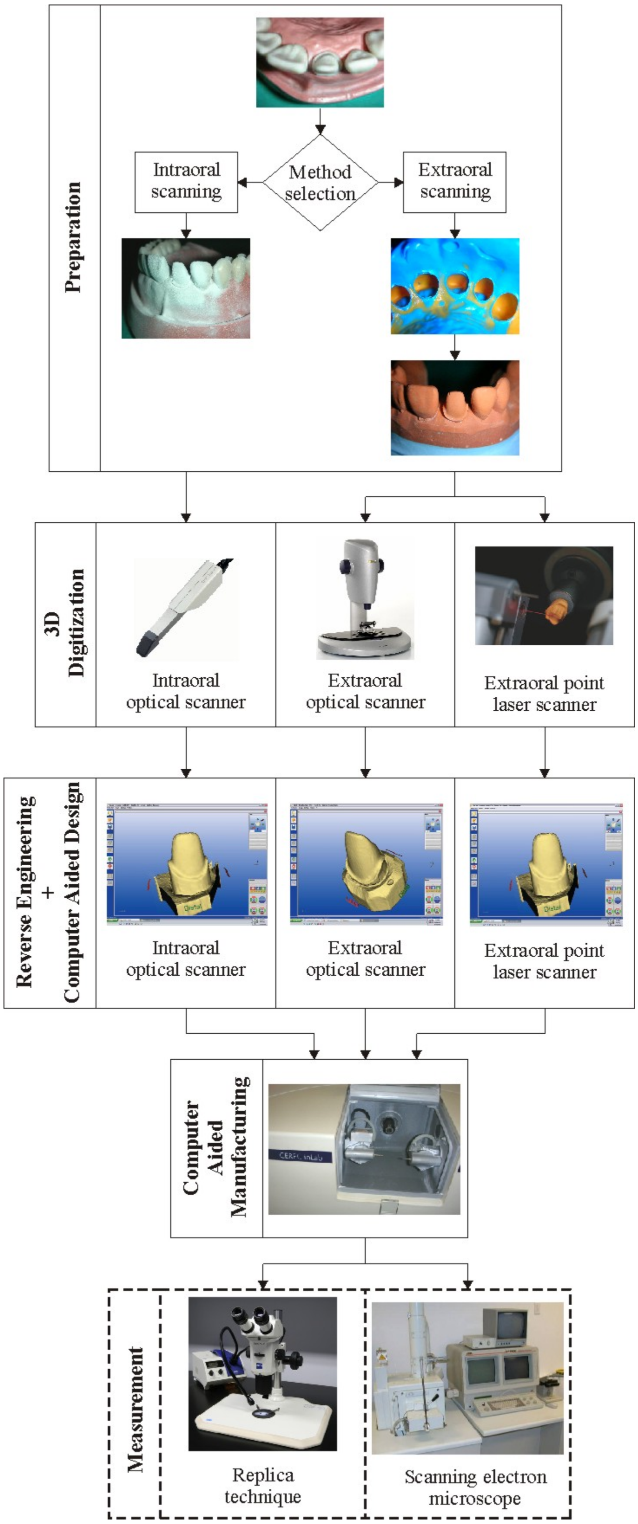


Fig.1. Workflow of the research methodology.

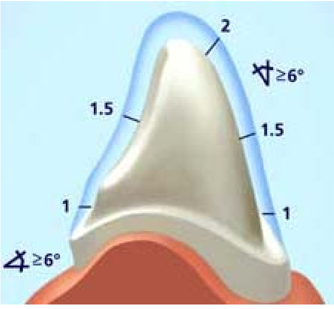


Fig.2. Design of crown preparation

Fig.3. Crown preparation

The preparation for intraoral scanning included application of a thin layer of powder (Cerec – powder, VITA, Bad Sackingen, Germany) onto the teeth within the operating model. Extraoral techniques of 3D digitization require casting of a plaster model (CAM STONE M, Siladent). For that purpose, the operating model teeth were used. The impression was taken using addition-silicone (A silicone impression material-elite HD+, ZHERMACK), and a monophase impression technique. Thus made, the plaster model was scanned using InEos and Cerec Scan scanners. Dental restorations were digitally modeled using Cerec software, v 3.10.

Once tooth preparation is completed, acquisition of geometry data from the physical object is performed, using 3D digitization or scanning. The methodology described in this paper was based on three types of 3D digitization systems from the Cerec family:

- intraoral optical scanner (IOS),
- extraoral optical scanner InEos (EOS), and
- extraoral point laser scanner (ELS).

Within this phase, surface coordinates on the physical object are acquired and converted into digital format. Point clouds acquired by 3D digitization are imported into the RE-CAD module in automated mode. The basic task of the RE-CAD module is to generate a complete CAD model of dental restoration. In order to allow optimum reconstruction of scanned surface, missing points are generated by interpolation. Once this process is completed, a mesh of the scanned object is generated. The inner contour of dental restoration is always automatically generated.

The major problem in CAD is the generation of outer contour of the model, especially in the case of occlusive crown surface. The modeling of occlusive surface of dental restoration can be done in the following ways: manually, using specialized software, and by selecting existing models from the database. The design solution of dental restorations was selected from the existing database (Fig.4). The primary reason for selecting the existing model from the database was to eliminate the subjective error introduced by the operator. In this way, it is possible to conduct a valid and reliable comparison between the results of measurement of the marginal gap of dental crowns. The dental database contains various sets of data which can be selected according to the specific situation.

Once the design solution is finalized, manufacturing begins. The crowns were machined using Cerec in Lab numerically controlled (NC) milling machine (Fig.5). To allow machining of ceramic crowns, ceramic blocks fixed on metal holders were used. Metal holders are fixed into the holder on the CNC milling machine. The CNC milling machine has two tool carriers which support two cutting tools that simultaneously machine the ceramic block. Crowns in all groups were made out of blocks of alumina ceramics (Vita Mark II, A3, Vita). Due to imperfect tooth preparation, tool path trajectory is approximated by cubic spline interpolation. Owing to their geometric continuity which the user perceives as smoothness, spline curves allow the system to compensate for eventual imperfections in tooth preparation. Using the selected scanning techniques 8 ceramic crowns were made for each of the groups. To minimize the influence of tool wear on the accuracy of dental restorations, each crown was machined with a set of new tools. In order to measure them, all samples had to meet the Ryge-Snyder criteria [24].

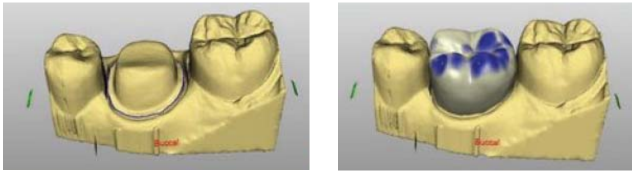
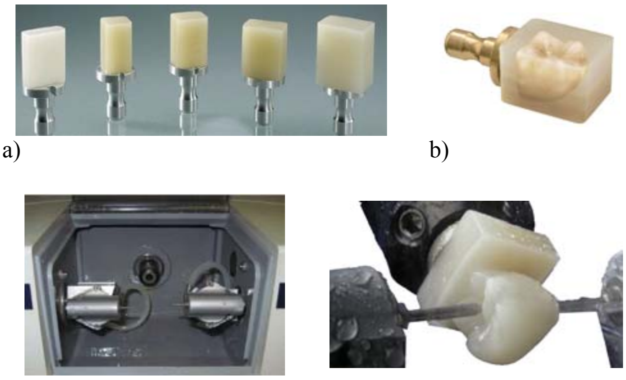


Fig. 4. Design of dental restoration.



a) b) c) d)

Fig.5. CAM-related components of the Cerec CAD/CAM system, a) ceramic blocks set on holders, b) ceramic block on the holder with the ceramic crown to be generated by machining, c) CNC milling machine workspace, d) detail of machining process.

3. RESULTS

Measurements of the marginal gap were performed on prepared models which were used to accommodate all manufactured dental restorations. On each experimental specimen 4 measuring points were defined – on the mesial surface, distal surface, vestibular surface and oral surface (Fig.6). All measurements were performed under identical experimental conditions using the same measuring devices.

Marginal gaps were measured using the replica technique and the scanning electron microscope. In both cases, a total of 8 marginal gap measurements were performed at each of the 4 measuring points, using the three scanning methods. Statistical analysis was performed in SPSS 17.0 for Windows (SPSS Inc., 2005). Kruskal-Wallis test was used for non-parametric analysis of variance, while Dunnett's test was used for comparison of group means.

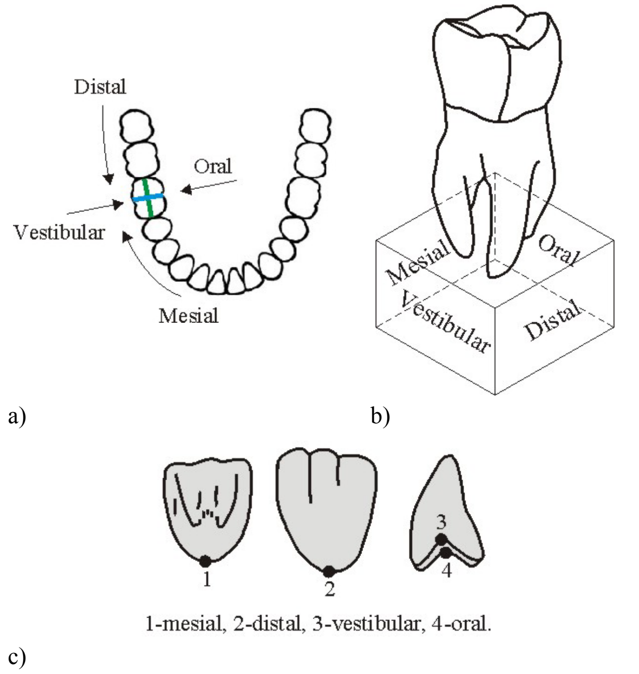


Fig.6. Diagrams of crown measurements, a) directions of measurements, b) characteristic surfaces, c) marginal gap measurement points.

A. Measurement results for marginal gaps – replica technique

Replica technique required the application of impression material based on addition-silicone. Addition-silicone of very low viscosity (ExpressTM2 Ultra-Light Body Quick) was applied to crown interior, after which the crowns were set onto basic samples. Impression material was polymerized within the time interval recommended by the manufacturer, while the pressure force of 50 N was applied in occlusal direction.

After the removal of crowns from the basic samples, a thin layer of impression material remained on the restoration's inner surface due to its higher roughness compared to the abutment surface. The thin layer of impression material represents a replica of space between the abutment and restoration. In order to stabilize this layer, low-viscosity addition-silicone of different color (ExpressTM2 Light Body Flow Quick) was applied inside the crown.

Upon completion of polymerization of the silicone impressions, they were cut by a sharp scalpel along buco-oral and mesiodistal directions. The prepared impressions were examined by stereo microscope (Stemi SVII, Karl Zeiss, Germany) in 4 pre-determined points on the mesial, distal, vestibular and oral surfaces (Fig.7). The measurements were performed by the same operator, as recommended by Holmes et al. [10].

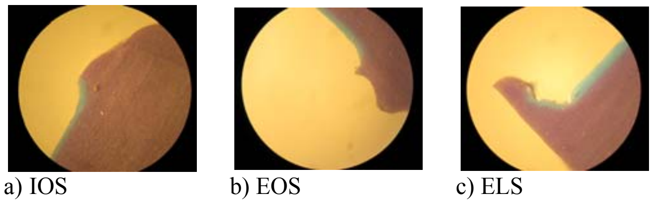


Fig.7. Surface of a cross section examined on stereo microscope.

Mean values of crown marginal gaps for each measuring point are shown in Table 1, while the aggregate values of crown marginal gaps are presented in Table 2.

Comparison between aggregate values of marginal gaps by Kruskal-Wallis test showed statistically significant differences ($p=0.000$) among the considered groups of crowns: ELS, IOS and EOS.

Comparison between marginal gaps in the considered groups by Dunnett's test revealed the following:

- marginal gaps obtained by ELS were statistically significantly greater than those of IOS ($p=0.000$), and EOS ($p=0.000$) scanning;
- marginal gaps obtained by IOS were statistically significantly greater than those of EOS ($p=0.000$) scanning.

Measurement Point	Groups	Mean	Median	Standard deviation	Minimum value	Maximum value	Number of samples	95% confidence interval
		(μm)	(μm)	(μm)	(μm)	(μm)	/	(μm)
1	ELS	95.85	96.81	5.83	83.73	102.13	8	90.97-100.73
	EOS	29.47	29.05	2.10	26.73	32.48	8	27.71-31.22
	IOS	39.67	39.38	1.92	37.61	42.71	8	38.06-41.27
2	ELS	96.39	96.10	4.04	90.83	101.99	8	93.01-99.76
	EOS	29.37	30.08	2.26	26.11	32.07	8	27.48-31.26
	IOS	39.82	40.50	2.18	36.31	42.22	8	37.99-41.64
3	ELS	96.84	96.77	2.90	92.61	100.73	8	94.42-99.27
	EOS	29.25	29.30	1.28	27.00	31.14	8	28.18-30.32
	IOS	39.53	40.27	2.16	35.00	41.88	8	37.72-41.33
4	ELS	96.48	96.98	3.06	92.22	100.38	8	93.91-99.04
	EOS	29.28	29.48	1.85	26.28	31.84	8	27.73-30.83
	IOS	39.62	39.17	1.70	37.08	41.83	8	38.20-41.04

Table 1. Mean values of crown marginal gaps at measurement points 1 - 4

Groups	Mean	Median	Standard deviation	Minimum value	Maximum value	Number of samples	95% confidence interval
	(μm)	(μm)	(μm)	(μm)	(μm)	/	(μm)
ELS	96.39	96.46	3.94	83.73	102.13	32	94.97-97.81
EOS	29.34	29.51	1.82	26.11	32.48	32	28.69-30.00
IOS	39.66	39.83	1.90	35.00	42.71	32	38.97-40.34

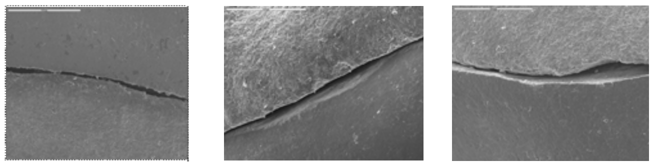
Table 2. Aggregate values of crown marginal gaps

B. Measurement results for marginal gaps – SEM

Preparation of experimental samples for measurement included fixation of crowns to the basic model by temporary cement (Rely XTM Temp NE, 3M ESPE). Within the time interval required for cement polymerization, the samples were subjected to an occlusal force of 50 N. Four measurement points were defined, one each per vestibular, oral, mesial, and distal surfaces. The points represented projections of points at which precision was previously measured using the replica technique.

Preparation for SEM consisted of a 4 min. coating of samples with gold in vacuum, by a standard metal evaporation technique. Marginal gap measurements were performed on JOEL JSM-5800 Scanning Microscope (Fig.1), with magnification factor of 100. Samples were scanned at pre-defined measurement points and the size of discrepancy between crown and demarcation of preparation was determined. Scanned images were edited in Image pro 40 software (Fig.8).

Mean values of crown marginal gaps obtained at measurement points are presented in Table 3, while the aggregate values are shown in Table 4.



a) IOS b) EOS c) ELS

Fig.8. Image of a sample examined on SEM.

Measurement Point	Groups	Mean	Median	Standard deviation	Minimum value	Maximum value	Number of samples	95% confidence interval
		(μm)	(μm)	(μm)	(μm)	(μm)	/	(μm)
1	ELS	102.82	103.54	5.98	93.81	109.42	8	98.68-106.96
	EOS	32.03	31.29	2.91	29.15	37.38	8	30.01-34.05
	IOS	49.15	49.31	4.67	42.35	57.16	8	45.91-52.39
2	ELS	101.94	102.89	6.28	91.43	109.22	8	97.59-106.29
	EOS	32.39	31.74	1.89	30.09	36.14	8	31.08-33.70
	IOS	47.61	47.74	4.24	41.32	53.39	8	44.67-50.55
3	ELS	101.75	104.06	5.64	92.70	107.16	8	97.84-105.66
	EOS	31.36	31.48	1.01	29.98	32.67	8	30.66-32.06
	IOS	47.26	47.72	5.04	40.52	55.13	8	43.77-50.75
4	ELS	100.73	101.93	5.24	91.11	106.32	8	97.10-104.36
	EOS	31.09	30.83	0.99	29.73	33.07	8	30.40-31.78
	IOS	46.66	47.21	5.11	39.00	54.27	8	43.12-50.20

Table 3. Mean values of crown marginal gaps at measurement points 1 – 4

Groups	Mean	Median	Standard deviation	Minimum value	Maximum value	Number of samples	95% confidence interval
	(μm)	(μm)	(μm)	(μm)	(μm)	/	(μm)
ELS	101.81	103.38	5.56	91.11	109.42	32	99.88-103.74
EOS	31.72	31.48	1.86	29.15	37.38	32	31.08-32.36
IOS	47.67	47.94	4.63	39.00	57.16	32	46.07-49.27

Table 4. Aggregate values of crown marginal gaps

Comparison between summary values of marginal gaps by Kruskal-Wallis test showed statistically significant differences (p=0.000) among the considered groups of crowns ELS, IOS and EOS.

Comparison between marginal gaps in considered groups by Dunnett's test revealed the following:

- marginal gaps obtained by ELS were statistically significantly greater than those of IOS (p=0.000), and EOS (p=0.000) scanning;
- marginal gaps obtained by IOS were statistically significantly greater than those of EOS (p=0.000) scanning.

C. Comparison between measurements of marginal gaps obtained by the replica technique and SEM

The results of comparison between measurements of marginal gaps obtained by the replica technique and SEM are presented in Table 5. The difference of -5.27 which is statistically significant according to non-parametric Wilcoxon signed-rank test (p=0.000), and parametric paired samples t-test (p=0.000), indicates significantly larger marginal gaps in crowns which were inspected by SEM in comparison to those inspected by the replica technique.

Group	Mean (μm)	Standard deviation (μm)	Minimum value (μm)	Maximum value (μm)	Number of samples /
Replica crowns	55.13	29.76	26.11	102.13	24
SEM crowns	60.40	30.46	29.15	109.42	24
Difference	-5.27				

Table 5. Comparison between measurements of marginal gaps obtained by the replica technique and SEM.

4. DISCUSSION

Presented investigation dealt with a comparison between marginal gaps of ceramic crowns made by the Cerec CAD/CAM system in vitro, using the replica technique and SEM.

Both of the tested methodologies have their advantages and disadvantages. Replica technique is a methodology applicable to in vitro [16,25] and in vivo [26] measurements of precision, whereas SEM is used exclusively in vitro [27,28]. Compared to SEM, the replica technique's advantage reflects in the fact that there is a small probability of damaging the sample and abutment in the process, which makes it a non-destructive methodology [29]. A relative disadvantage of this technique is the two-dimensional representation of results. However, the majority of authors agree that, compared to other techniques, the replica technique offers more possibility for veritable and accurate results [29,30].

The results of this investigation (Wilcoxon test (p=0.000)) and paired samples t-test (p=0.000) show that there is a statistically significant difference between marginal gaps in ceramic crowns inspected by the replica technique and SEM. In contrast to the results of this experiment, Rahme et al. did not report any statistically significant differences between marginal gaps measured by the replica technique and the thickness of cement film after its application, obtained by direct evaluation by light microscope [30].

Considering the direct evaluation of samples by microscope, it is important to emphasize the relevance of proper orientation of light beam relative to the inspected surface, especially when the demarcation shoulder angle exceeds 90º. In that case it is extremely difficult to locate the beam source relative to the sample. In the worst case scenario, the locating of light beam can deviate up to 30º. According to the cosine rule (Fig.9), h' is approximately 15% greater than the real value of marginal gap h [31]:

$$h \leq \frac{h'}{\cos\alpha} = h' \quad 1.15 \qquad (1)$$

where α=30º, h' is the measured marginal gap, and h is the real value.

When the samples are examined by light microscope, the previously described phenomenon can greatly influence the difference between the read and the real marginal gap values [31]. Groten's theory could also be applicable on marginal gap measurements by SEM. Furthermore, it could be used to explain the obtained results, i.e., the difference between the marginal gaps measured by the replica technique and SEM. In this investigation, proper positioning of samples during SEM was partially obstructed by the chamber which held the samples. It was closed and did not allow the positioning of samples to be performed in a controlled manner. It can be assumed that, due to a flat measurement surface, the sample could have been more accurately positioned if a tooth cross section were made. However, it should be noted that cutting of a sample involves the risk of surface damage which adversely affects the precision of measurements.

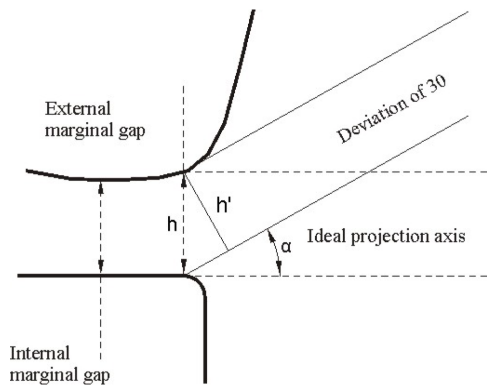


Fig.9. Schematic view of marginal gap measurement [31].

To a certain extent, SEM also suffers from variations in electron beam intensities which results in the differences between black and white graphic areas on the scanned samples. This represents a potential danger when it comes to accurate interpretation of results. According to Groten et al. the probability of error in SEM is about 10%, which is not accurate enough for marginal gap evaluation. On the other hand, they also emphasize the advantages of SEM in analysis of crown morphological structure and demarcation [31].

Arguably, the obtained results indicate that there are various accuracies of dental restorations obtained by various scanning techniques of the Cerec CAD/CAM system. The results obtained with the replica technique indicate the highest accuracy in crowns made by extraoral optical surface scanning (26.11-32.48 μm), followed by the crowns made by intraoral optical surface scanning (35.00-42.71 μm), and extraoral optical point scanning (83.73-102.13 μm). The identical order in terms of accuracy was reported in a paper which deals with the testing of accuracy of ceramic crowns made by the Cerec CAD/CAM system. The samples were evaluated by SEM, and following results were reported: extraoral optical surface scanning (31.64±9.45 μm), intraoral optical surface scanning (50.27±31.50 μm), and extraoral optical point scanning (102.58±31.23 μm) [32].

Replica technique is a reliable and accurate method for evaluation of accuracy of dental restorations, which also allows quantification of discrepancies on inner surfaces and marginal edge of the crown. In contrast to the replica technique, SEM is only fit for evaluations of marginal gaps, while inner surface fits are impossible to evaluate without cutting the sample, which can compromise the accuracy of this method. In that context, it is important to note the potentials of micro CT in accurate non-destructive evaluation of dental restoration fits [33].

5. CONCLUSIONS

Technical features of the Cerec CAD/CAM system which unifies three different methods of optical scanning, enabled identical computer-aided design and manufacturing procedures regardless of the scanning method employed. Thus, two input factors were held constant (computer-aided design and manufacture), while the influence of the third factor (3D digitization) on the process quality was investigated.

The results of this experiment indicate differences in marginal gap values in ceramic crowns manufactured by the Cerec CAD/CAM system, evaluated by the replica technique and SEM. The values of marginal fits in ceramic crowns evaluated by the replica technique were statistically significantly lower compared to the values obtained by SEM. The results indicate that the choice of technique for measuring the accuracy of ceramic crowns influences the final results of the investigation.

Further research will focus on application of micro CT dental systems in measurement of the marginal gap of ceramic crowns, with emphasis on comparative analysis of the results from all three methods.

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