Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

Maejo International Journal of Science and Technology

ISSN 1905-7873
Available online at www.mijst.mju.ac.th

Full Paper

Analysis of accuracy and precision of optical 3D digitisation devices in dental computer-aided-design and computer-aided-manufacturing systems

Branka Trifkovic [1], Igor Budak [2], Djordje Vukelic [2, *], Tatjana Puskar [3], Danimir Jevremovic [4] Aleksandar Todorovic [1], Ana Todorovic [1] and Srdjan Postic [1]

[1] University of Belgrade, School of Dentistry, Rankeova 4, 11000 Belgrade, Serbia
[2] University of Novi Sad, Faculty of Technical Sciences, Department of Production Engineering, Trg Dositeja Obradovica 6, 21000 Novi Sad, Serbia
[3] University of Novi Sad, Medical Faculty, Hajduk Veljkova 3, 21000 Novi Sad, Serbia
[4] University of Business Academy Novi Sad, Faculty of Stomatology, Zarka Zrenjanina 179, 26000 Pancevo, Serbia
* Corresponding author, e-mail: vukelic@uns.ac.rs

Received: 19 February 2016 / Accepted: 16 March 2017 / Published: 21 March 2017

Abstract: The implementation of intraoral and extraoral computer-aided-design and computer-aided-manufacturing (CAD/CAM) systems in prosthetic dentistry has simplified the procedure, shortened the period of design and manufacture and improved accuracy and aesthetic properties of dental restorations. Three-dimensional (3D) digitisation has become an adequate replacement for conventional dental impressions. The market offers a variety of diverse optical intraoral and extraoral CAD/CAM systems equipped with digitisation devices that are based on different working principles. The main goal of this research is to determine whether precision and accuracy differ among optical digitisation devices. The research includes five high-end devices: Cerec AC, Cerec InEos, Trios, KaVo Everest and Sinergia Scan. The evaluation methodology of the experiment is based on CAD inspection. The results, obtained from accuracy and precision measurements with tolerance levels of 0.01, 0.25 and 0.05 mm, indicate that there is a difference in accuracy and precision between optical digitisation devices based on different working principles.

Keywords: computer-aided design, computer-aided manufacturing, 3D digitisation, dental technology, dental equipment

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

INTRODUCTION

The adaptation of technical properties of industrial computer-aided-design and computer-aided-manufacturing (CAD/CAM) systems to the demands of dental practice has enabled their application in almost all areas of dentistry. CAD/CAM systems are comprised of three segments: 3D digitisation, CAD and CAM. The three-dimensional (3D) digitisation presents the first step in the fabrication of dental restorations with the application of CAD/CAM technology. It is well known that every phase of manufacturing in both the conventional and CAD/CAM systems generates errors that are a standard issue in the process. The resulting errors are cumulative and they influence interactions between the dental restorations and the surrounding tissue.

One of the parameters used to evaluate the quality of dental restorations is marginal sealing. Clinically acceptable values of marginal seals are 0.05-0.07 mm [1, 2]. There are authors who attribute the same values to dental resorations fabricated using CAD/CAM technologies. Persson et al. [3], Vlaar and Vanderzel [4], and Mehl and Hickel [5] published results stating that the digitisation device accuracy is, on average, < 0.02 mm. Considering the fact that manufacturing errors are cumulative, the accuracy of a 3D digitisation device should be significantly below the listed values for marginal seal. Trifkovic et al. [6] investigated the performance of two dental optical systems. Their results showed no statistically significant difference in precision, but a significant difference in accuracy, between the Cerec AC and Cerec InEos Blue digitisation devices. Nedelcu and Persson [7] evaluated the scanning accuracy and precision of four commercially available intraoral scanners. They examined the effects of different material properties on scan data. Their results showed significant differences between coating and no-coating scanners. Discussing the accuracy of digital impressions acquired by TRIOS and 3D progress intraoral scanners, Yang et al. [8] detected the fitness of single crowns based on digital impressions and compared these with stone cast images from D700 and InEos model scanners. Digital impressions showed better trueness and lower precision compared to model images. Lower accuracy occurred in marginal areas of digital impressions. Shim et al. [9] analysed the marginal and internal adaptation of restorations fabricated with different versions of the CAD/CAM software and found that, in comparison with the old version, the new version could be recommended for the fabrication of well-fitting crown restorations and for the appropriate regulation of the spacer parameter.

Jeon et al. [10] studied the repeatability of scans of stone models and impressions of abutment teeth using a blue LED scanner and compared the findings between different abutment teeth types. They indicated a high repeatability and suggested a possible clinical advantage of scanning impressions of different abutment teeth types. Kim et al. [11] evaluated the digitisation of alginate impressions by analysing differences in scan data between two types of impressions (alginate and rubber) taken from the master die and scan data for the master die. The results of their study showed that rubber impressions had greater accuracy than alginate impressions. Jeon et al. [12] analysed the repeatability of conventional impressions of abutment teeth digitised with white- and blue-light scanners and compared the findings for different types of abutment teeth. Evaluation of the scans of abutment teeth impressions revealed that the blue-light scanner exhibited better repeatability than the white-light scanner. Rudolph et al. [13] compared the accuracy of various intraoral and extraoral digitising systems. Analyses were based on prepared ceramic master dies and their corresponding virtual CAD models. The digitising systems showed differences in accuracy within ±20 μm. Only single teeth were used for comparison.

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

A more frequent application of CAD/CAM technology in dental practice and previous working experiences present a challenge for researchers to investigate its technical characteristics using a set of possibilities, with the goal to eliminate existing drawbacks and replace them with better technical solutions. A simplified procedure, shortened design and manufacture time, high degree of accuracy and improved aesthetic properties of dental restorations are the main reasons why intraoral and extraoral CAD/CAM systems have a significant position in prosthetic dentistry today [14]. Digitisation in 3D has become an adequate replacement for conventional impression. The term 3D digitisation describes a procedure where point data are acquired from the surface of the object in the form of coordinates, i.e. transferred into the digital form [15]. Fundamentally, it is a measuring procedure established on diverse working principles in accordance with the methods of mathematics and physics. The result of 3D digitisation is a set of points whose position is defined via coordinates and which are, due to the shape they occupy in space, usually referred as point cloud in the literature [16, 17].

The market today offers a number of diverse CAD/CAM systems for intraoral and extraoral digitisation. The present research investigated the following devices (Table 1): Cerec AC, Trios, Cerec InEos, KaVo Everest and Sinergia Scan. An overview of fundamental technical properties and working principles suggests the existence of significant differences in the approach to acquiring digitised data and the degree of their accuracy and precision. It is important to emphasise that there are few scientific and expert articles analysing these problems in the available literature.

Table 1. Technical characteristics of some CAD/CAM devices

Device	Imaging technique	Area of application	No. of cameras	Type of light
Cerec AC	Single image acquisition (active trioangulation)	Intraoral	One	Blue light
Trios	Confocal microscopy	Intraoral	One	Blue light
Cerec InEos	Single image acquisition (active trioangulation)	Extraoral	One	Blue light
KaVo Everest	Single image acquisition (active trioangulation)	Extraoral	One	Visible light
Sinergia Scan	Single image acquisition (active stereovision)	Extraoral	Two	Visible light

Considering the fact that the digitisation process of dental CAD/CAM systems is based on diverse working principles, the null hypothesis is: There is no difference in the accuracy and precision between devices for intraoral and extraoral optical digitisation. Consequently, the main research goal is to determine whether there is a difference in precision and accuracy among the optical digitisation devices analysed.

MATERIALS AND METHODS

The experimental research is based on the CAD inspection methodology for inspecting geometrical and dimensional deviations based on the application of CAD model parameters, whose usage is essential for evaluating the deviation of geometry of CAD experimental samples in relation to the geometry of the CAD master model. In order to minimise the deviations occurring during the 3D digitisation process, this research was performed under *in vitro* conditions. During the

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

experiment, comparison and deviation measurement were performed between the CAD master and CAD experimental models.

The CAD inspection procedure includes the following phases:

- Digitising the working model in order to generate CAD master and CAD experimental models;
- Inputting CAD master and CAD experimental models into the CAD inspection software;
- Positioning CAD experimental models in accordance with CAD master models in order to find mutual overlaps;
- Measuring the deviation of CAD experimental models in comparison with CAD master model.

Generation of CAD Master Model

The CAD master model was generated based on the working model's 3D digitisation using the Atos III Triple Scan system. The CAD master model was used as a reference model for the analysis of CAD experimental models. The generation of the CAD master model consisted of the following: teeth preparation; making the impression and manufacturing a working plaster model; digitising the working model; and creating the CAD master model. For this research, acrylic resin teeth (DSP-model teeth, Nos. 11, 14 and 16, KaVo, Germany) were placed into the basic study model (KaVo, Bilebach, Germany) for further grinding and impressing. Teeth were prepared as follows: an upper right central incisor as a ceramic crown; an upper right first premolar as a ceramic inlay; and an upper right first molar as a ceramic crown. The preparation was performed by a well-trained operator using high-speed grinding instruments.

The impression of the basic model was taken with A-silicones (Express TM2 Ultra – Light Body Quick, 3M ESPE) by applying the single-stage impression technique. The working model was moulded in plaster (Blue Die Stone, TechCeram) (Figure 1a). It has been previously shown that in this type of plaster there is no projected light penetration on the model surface, thus enabling a higher degree of digitisation accuracy. The production of the working model using this material enabled 3D digitisation without the application of matting powder. In this way the dimensional error caused by an additional layer of powder was avoided, and hence there was no inaccuracy related to the increase in object dimensions or the impairment of its original morphology. Twenty-four hours after moulding the working model, 3D digitisation was performed using the Atos III Triple Scan in accordance with defined conditions (air temperature 20±1ºC, humidity 55±10%) without the application of matting powder. This was followed by the creation of the CAD master model (Figure 1b), which involved point data preprocessing, generation of the polygonal network and surface segmentation. The procedure was preceded by an obligatory camera calibration.

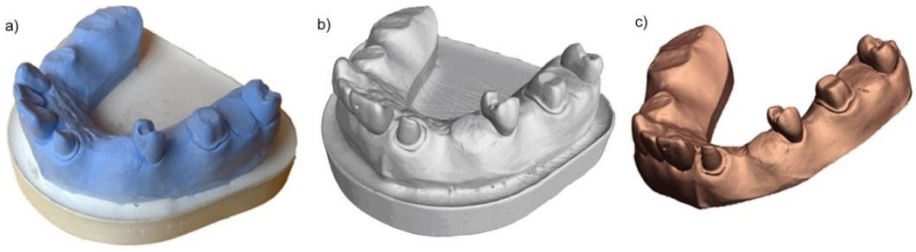

Figure 1. Models: a) plaster model; b) CAD master model; c) CAD experimental model

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

Generation of CAD Experimental Groups

The CAD experimental models were divided into 5 groups. Every experimental group comprised 10 samples of CAD experimental models. Experimental group samples originated from the 3D digitisation of the working model made of plaster using the following devices: group 1 – Cerec AC; group 2 – Trios; group 3 – Cerec InEos; group 4 – KaVo Everest; group 5 – Sinergia Scan. CAD experimental models (Figure 1c) were generated in STL file format, which can be taken as a standard data exchange format in dental applications.

CAD Inspection and Quantitative Analysis of Results

CAD inspection and quantitative analysis of the results were performed using GOM Inspect V7 SR2 software. After aligning the CAD experimental and master models by using best-fit algorithms, the distances between selected surfaces were calculated.

Results of the quantitative analysis were presented numerically using maps that show the defined deviation values in different colours. Deviations at tolerance levels 0.01, 0.25 and 0.05 mm were analysed. CAD inspection was performed by the application of GOM Inspect software, version V7 SR2.

RESULTS

The main comparison was conducted on a minimum tolerance level of 0.01 mm. Quantitative result analysis includes the following: analysis of precision, analysis of accuracy, and analysis of accuracy of the defined deviation values.

Statistical analysis includes the determination of standard deviation of mean values, 95% confidence intervals, mean values, minimum values and maximum values. The determination of statistically significant differences was performed with the application of the single-factor analysis of variance (ANOVA) test. The significance level was $p < 0.05$.

Quantitative result analysis includes the following:

- Result analysis related to precision;
- Result analysis related to accuracy;
- Result analysis related to accuracy of the defined deviation values.

Quantitative result analysis related to precision encompasses the comparison of mean values of the standard deviations of CAD experimental samples as compared to the CAD master model (Table 2). The highest mean standard deviation values were identified with Cerec AC (1.06119 mm), and the lowest with Sinergia Scan (0.66898 mm).

The value $p = 0.0000$ ($p < 0.05$) implies that the null hypothesis is discarded with 95% reliability (Table 3). There is a statistically significant difference in precision between the following devices: Cerec AC vs Cerec InEos, Cerec AC vs KaVo Everest, Cerec AC vs Sinergia Scan, Cerec AC vs Trios, Cerec InEos vs KaVo Everest, Cerec InEos vs Trios, Cerec InEos vs Sinergia Scan, KaVo Everest vs Sinergia Scan and Sinergia Scan vs Trios. There is no statistically significant difference in precision between KaVo Everest and Trios (Table 4). Quantitative result analysis related to accuracy encompasses the comparison of mean values of deviation of CAD experimental models and the CAD master model (Table 5).

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

Table 2. Measurement of precision between different optical digitisation devices

Device	Mean deviation (mm)	Standard deviation (mm)	Minimum value (mm)	Maximum value (mm)
Cerec AC	1.06119	0.044811	0.978342	1.14372
Cerec InEos	1.00571	0.0869435	0.904114	1.19405
KaVo Everest	0.726492	0.0451253	0.648914	0.791276
Sinergia Scan	0.66898	0.0193131	0.616537	0.688377
Trios	0.738792	0.00598507	0.729749	0.74726

Table 3. ANOVA results of precision

Source	Sum of squares	Degrees of freedom	Mean squares	F ratio	p
Between groups	1.2876	4	0.321901	133.99	0.0000
Within groups	0.108111	45	0.00240246		
Total	1.39572	49			

Table 4. Comparison of digitisation devices based on precision

Devices	Statistically significant difference	Value of difference	+/- Deviation limit
CerecAC – Cerec InEos	+	0.0554879	0.0441495
CerecAC – KaVo Everest	+	0.334702	0.0441495
CerecAC – Sinergia Scan	+	0.392215	0.0441495
CerecAC – Trios	+	0.322403	0.0441495
Cerec InEos – KaVo Everest	+	0.279215	0.0441495
Cerec InEos – Sinergia Scan	+	0.336727	0.0441495
Cerec InEos – Trios	+	0.266915	0.0441495
KaVo Everest – Sinergia Scan	+	0.0575122	0.0441495
KaVo Everest – Trios	-	-0.0122998	0.0441495
Sinergia Scan – Trios	+	-0.069812	0.0441495

Table 5. Measurement of accuracy between different optical digitisation devices

Device	Mean deviation (mm)	Standard deviation (mm)	Minimum value (mm)	Maximum value (mm)
Cerec AC	0.0896631	0.0201667	0.0597078	0.115497
Cerec InEos	0.0823524	0.0343604	0.00895235	0.121871
KaVo Everest	0.113692	0.0207142	0.0817615	0.1463
Sinergia Scan	0.0849243	0.00525558	0.0707482	0.0894347
Trios	0.121548	0.00225766	0.118028	0.12556

Results of the ANOVA test $p = 0.0001$ ($p < 0.05$) suggest that the null hypothesis is discarded with 95% reliability (Table 6). There is a statistically significant difference in accuracy between the following: Cerec AC vs KaVo Everest, Cerec AC vs Trios, Cerec InEos vs KaVo Everest, Cerec InEos vs Trios, KaVo Everest vs Sinergia Scan and Sinergia Scan vs Trios. There is no significant difference in accuracy between Cerec AC and Cerec InEos, Cerec InEos and Sinergia Scan, or KaVo Everest and Trios (Table 7).

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

Table 6. ANOVA results of accuracy

Source	Sum of squares	Degrees of freedom	Mean squares	F ratio	p
Between groups	0.0128512	4	0.0032128	7.84	0.0001
Within groups	0.0184422	45	0.000409826		
Total	0.0312934	49			

Table 7. Comparison of devices based on accuracy of digitisation procedure

Devices	Statistically significant difference	Value of difference	+/- Deviation limit
CerecAC – Cerec InEos	-	0.00731071	0.0182346
CerecAC – KaVo Everest	+	-0.0240288	0.0182346
CerecAC – Sinergia Scan	-	0.00473884	0.0182346
CerecAC – Trios	+	-0.0318849	0.0182346
Cerec InEos – KaVo Everest	+	-0.0313395	0.0182346
Cerec InEos – Sinergia Scan	-	-0.00257186	0.0182346
Cerec InEos – Trios	+	-0.0391956	0.0182346
KaVo Everest – Sinergia Scan	+	0.0287676	0.0182346
KaVo Everest – Trios	-	-0.00785606	0.0182346
Sinergia Scan – Trios	+	-0.0366237	0.0182346

Quantitative result analysis related to the accuracy of defined deviation values encompasses calculations for tolerance levels of 0.01, 0.025 and 0.05 mm (Tables 8-10, Figure 2). The obtained values are classified as follows by the server GOM Inspect V7 SR2:

- Positive fail – deviations 100% higher than the determined tolerance value;
- Positive warm – deviations from 75% to 100% of the determined tolerance value;
- Positive pass – deviations from 0% to 75% of the determined tolerance value;
- Negative pass – deviations from -75% to 0% of the determined tolerance value;
- Negative warm – deviations from -100% to - 75% of the determined tolerance value;
- Negative fail – deviations smaller than -100% of the determined tolerance value.

Table 8. Results of device accuracy with 0.01-mm deviation

Tolerance 0.01 mm	Cerec AC	Cerec InEos	KaVo Everest	Trios	Sinergia Scan
Positive fail (%)	22.20	24.07	11.40	14.92	22.78
Positive warm (%)	3.10	4.03	3.46	5.64	8.52
Positive pass (%)	10.08	14.87	21.36	30.06	39.29
Negative pass (%)	9.17	13.43	28.11	29.09	18.50
Negative warm (%)	2.46	3.26	7.75	5.83	2.76
Negative fail (%)	53.01	40.34	27.93	14.46	8.15

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

Table 9. Results of device accuracy with 0.025-mm deviation

Tolerance 0.025 mm	Cerec AC	Cerec InEos	KaVo Everest	Trios	Sinergia Scan
Positive fail (%)	11.08	13.36	4.35	5.69	4.78
Positive warm (%)	2.56	2.35	1.35	1.42	3.54
Positive pass (%)	21.73	27.26	30.5	43.52	62.28
Negative pass (%)	17.35	23.17	50.6	44.50	25.78
Negative warm (%)	2.46	1.98	5.97	2.20	1.19
Negative fail (%)	44.82	31.88	7.14	2.68	2.43

Table 10. Results of device accuracy with 0.05-mm deviation

Tolerance 0.05 mm	Cerec AC	Cerec InEos	KaVo Everest	Trios	Sinergia Scan
Positive fail (%)	9.07	10.63	3.35	4.23	2.20
Positive warm (%)	0.59	0.91	0.23	0.45	0.49
Positive pass (%)	25.71	31.43	32.63	45.94	67.90
Negative pass (%)	22.40	26.82	61.97	48.27	27.92
Negative warm (%)	0.99	0.63	1.11	0.45	0.36
Negative fail (%)	41.24	29.57	0.70	0.65	1.12

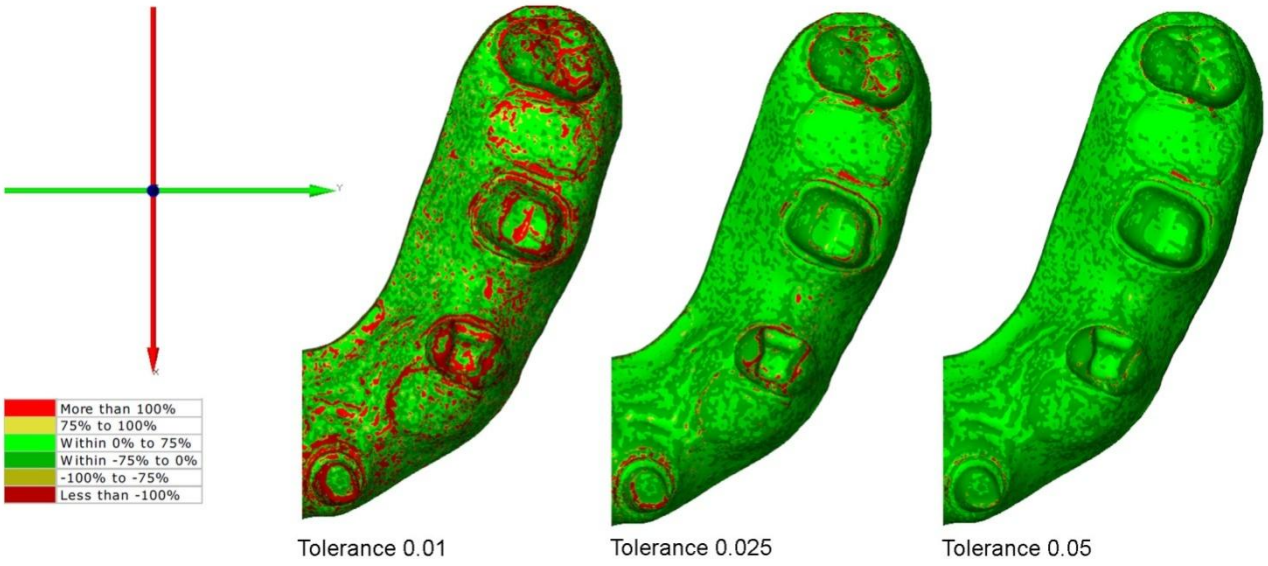

Figure 2. Examples of map of colour regions

DISCUSSION

Many of the 3D digitisation devices examined in this study do not have any available manufacturer or literature information on accuracy and precision. The manufacturer's estimation of the accuracy of the Cerec InEos and Cerec AC cameras are identical (≤ 0.019 mm), but data on their precision are not available. There is no manufacturer or literature information on the accuracy or precision of the Trios device. The manufacturer's stated accuracy of KaVo Everest is ≤ 0.035 mm, and for Sinergia Scan it is ≤ 0.012 mm, though there is no record of their accuracy and precision in published expert and scientific papers. Based on the information from the manufacturer, the precision of the Sinergia Scan device is < 0.002 mm. Mehl et al. [18] confirmed that the environment does not affect the degree of accuracy and precision of 3D digitisation devices.

Maejo Int. J. Sci. Technol. **2017**, *11*(01), 45-57

In contrast to extraoral digitisation, there are no conventional impressions or stone replicas manufactured in the intraoral digitisation procedure [19]. Since intraoral digitisation presents the replacement of conventional impression, Ender and Mehl [20] believe that accuracy and precision of intraoral digitisation must be equivalent to the degree of accuracy and precision of a conventional impression.

When comparing the results of several studies dealing with this problem, one should be careful about the applied digitisation methods. Brosky et al. [21] reported that the discrepancy between the model manufactured by the conventional impression procedure using the A-silicone and the reference CAD model ranged between 0.027-0.279 mm. Some studies compared the accuracy of conventional impressions of a group of teeth or an individual tooth with that of the 'virtual impressions' of the same objects. Luthardt et al. [22] stated that the accuracy of the 3D digitisation of a group of teeth using the Cerec 3D camera was 0.028 mm, while that of conventional impressions using A-silicones was 0.018 mm. The same author stated that the accuracy of the Cerec 3D camera in the process of 3D digitisation of one tooth was 0.025 mm while the accuracy of the Cerec AC camera was better (0.019 mm) [18].

The accuracy of conventional and virtual impression procedures can be observed indirectly as well, by measuring the value of the marginal gap between the preparation of demarcation and dental restoration [19, 23]. In this case the marginal gap represents a parameter that results from summarising errors occurring during the entire manufacturing process, including not only errors occurring in the process of 3D digitisation, but also those occurring in the computer design and production of restorations.

Precision Difference between 3D Digitisation Devices

Due to the specificity of the experiment, the mean values of standard deviations represent parameters used for precision classification. In this study the highest mean standard deviations were observed with the Cerec AC device, consistent with its low degree of precision. These results may be explained by the difference in technical properties of the devices. The Sinergia Scan possesses two cameras and the ratio between cameras and objects is defined, which is a prerequisite for providing a high degree of precision.

The camera in the Cerec AC is positioned in the operator's hands, which can cause trembling or improper object positioning within the measurement volume of the camera. Improper positioning of the object forms an inadequate angle between the object and the camera and influences precision and accuracy. The presumption is that the Sinergia Scan has a greater measurement volume (200 x 200 x 200 mm^2) as compared to the Cerec AC and Cerec InEos, although there are no available data to support this. A greater measurement volume provides more possibilities for proper object positioning within it, providing a higher degree of precision and accuracy.

In comparison to the devices for extraoral digitisation, intraoral devices have a lower degree of precision, consistent with the idea that manual positioning (Cerec AC) or camera movement (Trios) influences the quality of the digitised data. The low degree of precision of intraoral devices, as observed in this study, casts doubt on the manufacturer's recommendation.

The Trios device is based on the working principles of confocal microscopy. A low degree of precision can result from the drawbacks of the technical properties of the devices or from the 3D digitisation methodology. In contrast to the Cerec AC, for which the manufacturer provides accurate data on the application method (distance between the camera and the object, triangulation angle),

similar information is not provided for the Trios devices. This information is especially important if regarded in the context of everyday clinical usage of the Trios devices, since it can present an indicator of reliability.

In the process of 3D digitisation with Cerec InEos, the manual movement of the model in relation to the camera was performed. One of the possible explanations of a low degree of precision is the applied digitisation methodology and the procedure of the formation of the 3D image. The software in the Cerec system creates an image by merging a larger number of individual images. The assumption is that the process of image alignment and merging can cause deviations. The low degree of precision of Cerec AC and Cerec InEos in comparison with other devices can also stem from the quality of camera. A statistically significant difference in precision between these two devices and a higher degree of precision of Cerec InEos indicate the qualities and advantages of extraoral (Cerec InEos) digitisation over intraoral (Cerec AC) digitisation.

Accuracy Difference between 3D Digitisation Devices

The lack of statistically significant difference in the accuracy of Cerec cameras is expected, considering the fact that they have identical technical performance. A high degree of accuracy is one of the indicators of good technical properties of a camera. The accuracy of Cerec AC was found to be significantly higher than that of the Trios device, suggesting that the Cerec AC possesses better technical properties and digitisation methodology. The high degree of accuracy observed for the Sinergia Scan device confirms the quality of this extraoral digitisation device with two cameras.

The results of device accuracy obtained in our study differ from some other published results. Ender and Mehl [20], for example, demonstrated that the accuracy of Cerec AC in the digitisation of the upper jaw dental arch was 0.049 ± 0.0142 mm. However, the results of the present study demonstrate an accuracy of Cerec AC that is nearly twice that value (0.0823 mm). The accuracy of 3D digitisation devices is largely determined by the density of the point cloud and the quality of the virtual model processing procedure. An important parameter influencing the accuracy is the calibration of the digitisation device.

Devices with higher resolution have also been shown to have better accuracy. The manufacturers' information states that there is a difference in resolution between Sinergia Scan and Cerec cameras. Since data on the resolution of the Sinergia Scan device are presented as triangles (2,000,000 triangles), while Cerec data are in mm (0.025 x 0.025 mm – the size of a pixel), it is not possible to objectively compare the parameters presented in different units. However, the results of our research show that despite a somewhat higher degree of accuracy of Cerec InEos in comparison to Sinergia Scan, there is no statistically significant difference between the values representing their accuracy. This suggests that camera resolution influences the accuracy of digitised data.

One should be careful when defining the final grade of 3D digitisation device quality. Accuracy is a parameter related to the scanned object dimensions, while precision represents the equivalent of the everyday use of devices. A device can qualify as being precise despite the consistent measurement of a value that does not coincide with the real object dimensions. A reliable 3D digitisation can be realised exclusively with devices that are both extremely accurate and precise.

Accuracy Difference in Defined Deviation Values between 3D Digitisation Devices

The lowest deviation found in this research is 0.01 mm. The difference between the CAD experimental model and CAD master model at this tolerance level presents an accuracy degree that

is significant for explaining the technical performance of the devices. The tolerance level of 0.025 mm indicates an average space thickness for a cement film [24, 25]. The deviation of 0.05 mm indicates an accuracy in the zone whose value presents the average value of discrepancy between the grinded tooth and the implant [26, 27].

Cerec AC showed a high percentage of deviation in the area of negative fail at all tolerance levels. The decrease in deviation was not proportional to the increase in tolerance values. We believe this can be explained by the presence of errors occurring in the virtual model generation procedure within the software or deviations occurring in the alignment of the CAD experimental model and CAD master model. The sum of positive and negative pass values for the 0.05-mm deviation was smaller than 50% (48.11%). As previously mentioned, Cerec AC showed the highest degree of accuracy at the tolerance level of 0.05 mm, which is inadequate for clinical usage. However, if we compare the average values of accuracy for Cerec AC in the digitisation procedure for the right part of the upper jaw, the minimal deviation is 0.0598 mm and the maximal deviation is 0.1154 mm (average 0.0896 mm). The distribution of results explains the low deviations of positive and negative pass at the tolerance level of 0.05 mm, suggesting that Cerec AC is much more accurate at higher levels of tolerance. At the tolerance level of 0.01 mm, Cerec InEos has a high percentage of deviation within the negative fail (40.34%). In comparison, the deviations in the same area are lower for Cerec AC.

The sum of positive and negative pass values in the tolerance zone of 0.05 mm was found to range from 94.66%, indicating a high degree of accuracy for the KaVo Everest device at this tolerance level. The distribution of the results of positive fail for the Trios device is completely different from that for the Cerec system, where negative fail values are present in a much larger percentage. The lower percentage of negative fail for the Trios device may be an indicator of the software quality. The maximum percentages of positive (45.94%) and negative (48.27%) passes were found to occur in the tolerance zone of 0.05 mm. Their sum was 94.21%, which is somewhat lower than the sum for KaVo Everest.

The results for the Sinergia Scan device indicate a somewhat higher positive fail in comparison to negative fail values. The maximum values of positive (67.90%) and negative (27.92%) passes were found to occur in the tolerance zone of 0.05 mm. Their sum was 97.82%, which is the highest value of all devices measured in this study, demonstrating once again the high degree of accuracy of the Sinergia Scan device.

CONCLUSIONS

Based on the overall research results, we conclude that there is a difference in the accuracy and precision among the optical digitisation devices with dental CAD/CAM systems where the 3D digitisation procedure is established based on diverse working principles. Devices for extraoral digitisation show a higher degree of accuracy and precision in comparison to devices for intraoral digitisation. The recommendation is to use intraoral digitisation devices in clinical cases where there is a demand to manufacture implants of smaller dimensions (inlays, onlays, single crowns, bridges up to three members, endocrowns, etc.), while in the case of large reconstructive processes (circular and semi-circular bridges), the use of extraoral digitisation devices is recommended. The results of our study also indicate that digitisation based on the principles of active triangulation, using the point-and-click technology for creating an image, has a much higher degree of accuracy relative to the technologies that employ video recording during the digitisation procedure. Experimental results have demonstrated that extraoral digitisation devices with two cameras have a

higher degree of accuracy and precision. Future research should aim to improve the accuracy and precision of the existing extraoral CAD/CAM systems, and open new opportunities by introducing a second camera into the digitisation process.

ACKNOWLEDGEMENT

This research was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

REFERENCES

1. H. W. Denissen, J. M. van der Zel and M. A. van Waas, "Measurement of the margins of partial-coverage tooth preparations for CAD/CAM", *Int. J. Prosthodont.*, **1999**, *12*, 395-400.
2. J. Tinschert, G. Natt, W. Mautsch, H. Spiekermann and K. J. Anusavice, "Marginal fit of alumina-and zirconia-based fixed partial dentures produced by a CAD/CAM system", *Oper. Dent.*, **2001**, *26*, 367-374.
3. A. Persson, M. Andersson, A. Oden and G. Sandborgh-Englund, "A three-dimensional evaluation of a laser scanner and a touch-probe scanner", *J. Prosthet. Dent.*, **2006**, *95*, 194-200.
4. S. T. Vlaar and J. M. van der Zel, "Accuracy of dental digitizers", *Int. Dent. J.*, **2006**, *56*, 301-309.
5. A. Mehl and R. Hickel, "A new optical 3D-scanning system for CAD/CAM technology", *Int. J. Comput. Dent.*, **1999**, *2*, 129-136.
6. B. Trifkovic, I. Budak, A. Todorovic, D. Vukelic, V. Lazic and T. Puskar, "Comparative analysis on measuring performances of dental intraoral and extraoral optical 3D digitization systems", *Measurement*, **2014**, *47*, 45-53.
7. R. G. Nedelcu and A. S. K. Persson, "Scanning accuracy and precision in 4 intraoral scanners: An *in vitro* comparison based on 3-dimensional analysis", *J. Prosthet. Dent.*, **2014**, *112*, 1461-1471.
8. X. Yang, P. Lv, Y. Liu, W. Si and H. Feng, "Accuracy of digital impressions and fitness of single crowns based on digital impressions", *Materials*, **2015**, *8*, 3945-3957.
9. J. S. Shim, J. S. Lee, J. Y. Lee, Y. J. Choi, S. W. Shin and J. J. Ryu, "Effect of software version and parameter settings on the marginal and internal adaptation of crowns fabricated with the CAD/CAM system", *J. Appl. Oral Sci.*, **2015**, *23*, 515-522.
10. J. H. Jeon, I. D. Jung, J. H. Kim, H. Y. Kim and W. C. Kim, "Three-dimensional evaluation of the repeatability of scans of stone models and impressions using a blue LED scanner", *Dent. Mater. J.*, **2015**, *34*, 686-691.
11. S. R. Kim, W. S. Lee, W. C. Kim, H. Y. Kim and J. H. Kim, "Digitization of dental alginate impression: Three-dimensional evaluation of point cloud", *Dent. Mater. J.*, **2015**, *34*, 835-840.
12. J. H. Jeon, B. Y. Choi, C. M. Kim, J. H. Kim, H. Y. Kim and W. C. Kim, "Three-dimensional evaluation of the repeatability of scanned conventional impressions of prepared teeth generated with white- and blue-light scanners", *J. Prosthet. Dent.*, **2015**, *114*, 549-553.
13. H. Rudolph, H. Salmen, M. Moldan, K. Kuhn, V. Sichwardt, B. Wostmann and R. G. Luthardt, "Accuracy of intraoral and extraoral digital data acquisition for dental restorations", *J. Appl. Oral. Sci.*, **2016**, *24*, 85-94.

14. I. Budak, B. Trifkovic, T. Puskar, D. Vukelic, V. Vucaj-Cirilovic, J. Hodolic and A. Todorovic, "Comparative analysis of 3D digitization systems in the field of dental prosthetics", *Tehn. Vjesnik*, **2013**, *20*, 291-296.
15. S. Klancnik, M. Ficko, J. Balic and I. Pahole, "Computer vision-based approach to end mill tool monitoring", *Int. J. Simul. Model.*, **2015**, *14*, 571-583.
16. I. Budak, D. Vukelic, D. Bracun, J. Hodolic and M. Sokovic, "Pre-processing of point-data from contact and optical 3D digitization sensors", *Sensors*, **2012**, *12*, 1100-1126.
17. C. Cajal, J. Santolaria, D. Samper and A. Garrido, "Simulation of laser triangulation sensors scanning for design and evaluation purposes", *Int. J. Simul. Model.*, **2015**, *14*, 250-264.
18. A. Mehl, A. Endler, W. Mormann and T. Attin, "Accuracy testing of a new intraoral 3D camera", *Int. J. Comput. Dent.*, **2009**, *12*, 11-28.
19. A. Syrek, G. Reich, D. Ranftl, C. Klein, B. Cerny and J. Brodesser, "Clinical evaluation of all-ceramic crowns fabricated from intraoral digital impressions based on the principle of active wavefront sampling", *J. Dent.*, **2010**, *38*, 553-559.
20. A. Edner and A. Mehl, "Full arch scans: Conventional versus digital impressions – an *in-vitro* study", *Int. J. Comput. Dent.*, **2011**, *14*, 11-21.
21. M. E. Brosky, R. J. Major, R. DeLong and J. S. Hodges, "Evaluation of dental arch reproduction using three-dimensional optical digitization", *J. Prosthet. Dent.*, **2003**, *90*, 434-440.
22. R. G. Luthardt, R. Loos and S. Quaas, "Accuracy of intraoral data acquisition in comparison to the conventional impression", *Int. J. Comput. Dent.*, **2005**, *8*, 283-294.
23. M. R. Baig, K. B.-C. Tan and J. I. Nicholls, "Evaluation of the marginal fit of a zirconia ceramic computer-aided machined (CAM) crown system", *J. Prosthet. Dent.*, **2010**, *104*, 216-227.
24. S. Valderrama, N. van Roekel, M. Andersson, C. J. Goodarcre and C. A. Munoz, "A comparison of marginal and internal adaptation of titanium and gold - platinium - palladium metal ceramic crowns", *Int. J. Prosthodont.*, **1995**, *8*, 29-37.
25. M. S. Jacobs and A. S. Windeler, "An investigation of dental luting cement solubility as a function of the marginal gap", *J. Prosthet. Dent.*, **1991**, *65*, 436-442.
26. P. Pera, S. Gilodi, F. Bassi and S. Carossa, "In vitro marginal adaptation of alumina porcelain ceramic crowns", *J. Prosthet. Dent.*, **1994**, *72*, 585-590.
27. M. Groten, S. Girthofer and L. Probster, "Marginal fit consistency of copy-milled all-ceramic crowns during fabrication by light and scanning electron microscopic analysis in vitro", *J. Oral Rehabil.*, **1997**, *24*, 871-881.