An Innovative Method for Evaluation of the 3-D Internal Fit of CAD/CAM Crowns Fabricated After Direct Optical Versus Indirect Laser Scan Digitizing

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Purpose: A procedure for 3-D analysis of the internal fit of fixed restorations has been developed. This study tested this method for investigating the fit of all-ceramic crowns. ***Materials and Methods:*** Twelve data sets of a prepared maxillary canine were acquired by direct digitizing of the metal master die (CEREC 3 camera) and by digitizing gypsum dies after conventional impression taking (CEREC 3 scan), respectively. Using these data sets, 24 all-ceramic single crowns each were machined out of two glass-ceramics. The method is based on duplicated gypsum dies of the metal master, which were made for each crown. The space between the duplicate die and the internal surface of the respective crown was filled with a low-viscosity addition silicone. These silicone films (replicas) and their corresponding dies were digitized in the same measuring position. The internal fit was calculated and quantitatively and qualitatively analyzed. ***Results:*** The mean and maximum positive deviations were 348 µm and 986 µm (camera), respectively, and 294 µm and 830 µm (scan), respectively, for Vitablocs Mk II and 332 µm and 920 µm (camera), respectively, and 307 µm and 852 µm (scan), respectively, for ProCAD. For both systems, the deviations were highest at the edges. CEREC scan yielded significantly better internal fit accuracy compared to the CEREC camera. ***Conclusion:*** Evaluation of the internal 3-D fit using the innovative method proved to be suitable. Indirect data acquisition using impression taking showed improved internal fit compared with the direct procedure. However, the differences between the data-acquisition techniques are small compared to their absolute values. *Int J Prosthodont 2004;17:680–685.*

The internal and marginal fit are paramount factors for quality assessment of fixed restorations.[1–3] Clinical trials have underlined the importance of marginal accuracy for clinical success.[1,4] Examinations dealing with the fit of crowns are mostly limited to their marginal accuracy.[5] Studies investigating the internal fit are based on measurements of sectioned teeth.[6,7] Because of the methodology, these measurements are limited to distinct points. Kelly et al[8] introduced a method based on three-dimensional mapping of the crown fit by using a non-destructive optical technique. Reflected light transmission through varying thicknesses of a colored impression material has been validated in comparison with cross-sectioned crowns. For the 3-D analysis of dental materials or procedures with higher resolution, digital data acquisition is required.[9–12] A computer-aided design (CAD) surface model and its identical metal master die have been applied for the assessment of the changes in die materials over time.[13] A preliminary study investigating the internal fit using a 3-D approach has been published.[14] Methodologic studies on

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3-D methods for the evaluation of the space between the prepared tooth and the entire internal surface of crowns are conspicuously lacking.

In the application of CAD/computer-aided manufacturing (CAM) techniques, the manufacturing of the restorations is performed either in the dental laboratory using conventional techniques or chairside based on the intraoral data acquisition. The idea of intraoral data acquisition is to substitute the conventional impression taking with an optical impression and avoid errors caused by the conventional impression procedure. To avoid reflections negatively influencing the intraoral digitizing, CEREC powder (Vita) has to be applied to the teeth to be digitized. The CEREC 3 system (Sirona) facilitates direct intraoral (CEREC camera) as well as indirect extraoral (CEREC scan) data acquisition. The technology has been described elsewhere.[15] Two different ceramic materials—the conventional glass-ceramic CEREC Vitablocs Mark II (Vita) and the leucite-reinforced glass-ceramic ProCAD (Ivoclar Vivadent)—are used for the fabrication of inlays, onlays, and single crowns. Most studies dealing with the fit of CEREC restorations have focused on inlays; only a few have examined the fit of CEREC crowns.[14,16]

This study was undertaken to test an innovative method for evaluation of the internal 3-D fit of crowns, investigating all-ceramic crowns fabricated with the CEREC 3 system. The methods of data acquisition (CEREC camera and CEREC scan) and the ceramic material used (Vitablocs Mk II and ProCAD), which might affect the fit, were taken into consideration. The specific aims of this study were to test the hypotheses that: *(1)* the method for evaluation of the internal 3-D fit is suitable, and *(2)* the 3-D internal fit of crowns is not influenced by the data-acquisition procedure or ceramic material used.

Materials and Methods

Data Acquisition

A metal master die of a maxillary right canine prepared with a circular chamfer and its identical CAD surface model were used for the experiments. Since adjacent teeth are required for the design of the restoration by the CEREC software, maxillary right lateral incisor and first premolar denture teeth from a teaching model (Frasaco, Franz Sachs) were fixed with wax adjacent to the metal master die. CEREC powder was applied to all surfaces using the CEREC propellant to avoid reflection and achieve correct data sets. The CEREC camera was mounted to a tripod above the modified master model and aligned according to the manufacturer's instructions. Twelve measurements were performed to produce 12 data sets.

An impression was made of the metal master die using the two-stage putty-wash technique (Impregum Penta and Permadyne Garant 2:1, ESPE). The impression was poured 8 hours after being made in type IV die stone (Fujirock EP, GC) at room temperature. The stone die was removed from the impression 4 hours later. Excess stone was removed by means of dry trimming to avoid contamination with water. The lateral incisor and caninedenture teeth were fixed adjacent to the stone die as described above. The modified stone model was fixed on the holder of the CEREC scan device and aligned manually according to the manufacturer's recommendations using the gauge. After CEREC powder was applied to the surfaces, the modified stone model was fixed inside the measurement chamber of the CEREC device and measured 12 times.

Design and Grinding of Crowns

Twelve crowns each were designed for both data-acquisition procedures using the database mode by encircling the equators of the neighboring teeth and tracing the baseline. The selected restoration was adapted by the integrated tooth database to the anatomic situation of the neighboring teeth. In the design process, the automatically calculated construction of the crown was accepted. In all, 48 crowns were ground using the CEREC 3 device—24 conventional glass-ceramic Vitablocs Mk II crowns and 24 leucite-reinforced glass-ceramic ProCAD crowns. For each material, 12 crowns were fabricated from the direct data sets and 12 were fabricated from the indirect data sets. The thickness of the spacer was set to 0 µm. Prior to the experiments, a new diamond tool (diameter 1.6 mm) was mounted, and new cooling agent (Dentatec, Sirona) was used. Diamond tools and cooling agent were changed whenever indicated by the CEREC 3 device. The fit of the milled crowns was checked on the metal master die using the fit-checker technique. Corrections were made using a light microscope. Interfering contacts were removed with a diamond bur. The time for adjustment was limited to 3 minutes per crown.

Measurement of Internal Fit

The aim of the procedure was the 3-D analysis of the internal space between the crowns and the metal master die (Fig 1, a´). For technical reasons, metal surfaces and cavities cannot be optically measured with high accuracy. Therefore, an indirect technique was developed, using gypsum duplicate dies instead of the metal master as well as silicone films (replicas) representing the internal surface of the crowns (Fig 1, c). The gypsum copy dies therefore represent the metal master die as well as the identical CAD surface model (Fig 1, a),

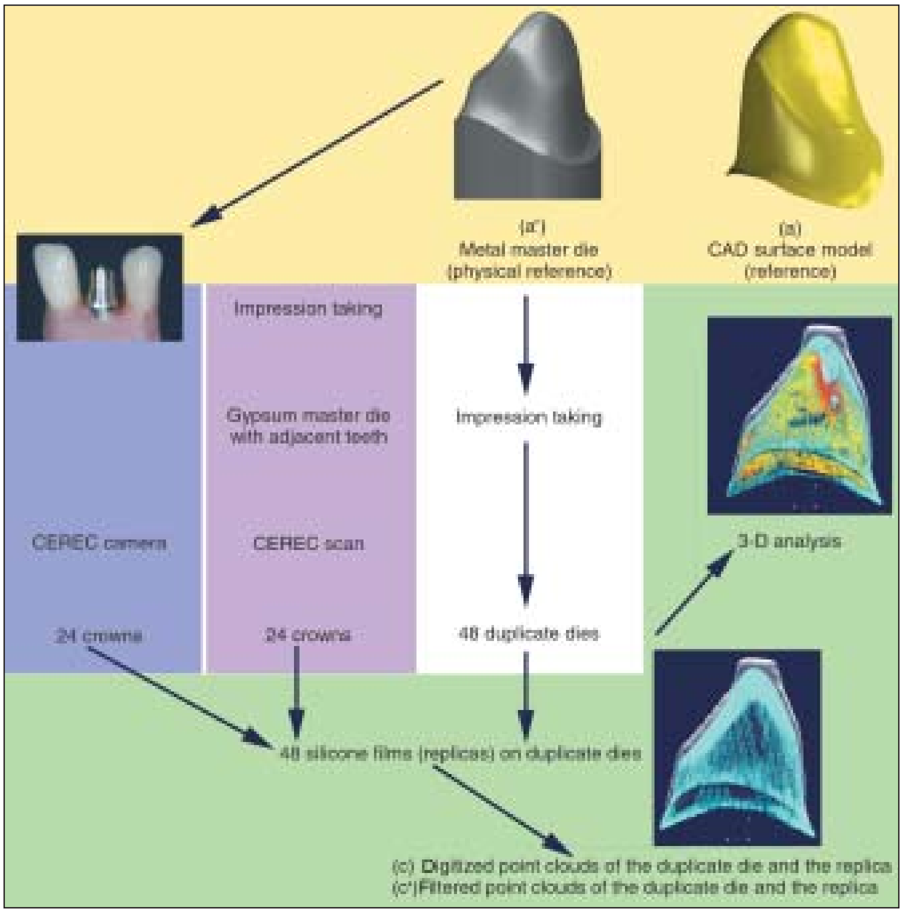

Fig 1 Method used for estimating internal 3-D fit of crowns; *yellow area* = reference; *green area* = evaluation; *blue area* = CEREC camera; *purple area* = CEREC scan.

whereas the external surface of the replicas represents the internal surface of the crowns.

Forty-eight copy dies were manufactured from the metal master die using the simultaneous technique as described above. Adhesive commonly used for impression trays was applied to the area below the finish line. The crowns were filled with a low-viscosity addition silicone (President Plus Light Body, Coltène Whaledent) to fill the space between the internal surface of the crowns and the surface of the die. During the setting time, a load of 20 N was applied to the crowns to standardize the procedure. The replicas and the respective dies were digitized (Fig 1) in a two-step procedure in an identical position in the same coordinate system of the measuring device (ODKM 97, IVB; Fraunhofer Institute for Applied Optics and Precision Engineering). The measuring device, including its basic principles, has been described elsewhere.[13,17] The measurement uncertainty given by the manufacturer is $\leqslant$ 8 µm. Evaluation and editing of the point clouds were done using ARGUS software (Fraunhofer Institute for Applied Optics and Precision Engineering). The raw point clouds of the master dies contained points located above and below the finish line. The raw point clouds of the replica contained points located on the inner and outer surfaces of the crown. Because of the measurement uncertainty, both raw clouds contained scattered points localized at various distances from the relevant points. Therefore, the point clouds were modified manually and filtered to reduce the data set to a point cloud of high accuracy (Fig 1, c´) as described elsewhere.[13] After transferring the data files to Surfacer (version 9.0, Imageware), both point clouds were reduced to about 45,000 points.

Registration is the process of bringing geometric entities into proper alignment. It is needed whenever an existing CAD surface model must be aligned with digitized data of the gypsum copy dies measured in a different coordinate system. Proper best-fit registration of the point clouds to the reference (CAD surface model; Fig 1) is required for the quantitative analysis of the internal fit using the point clouds of the replica. For the best-fit registration of the filtered point cloud of the gypsum die to the reference (CAD surface model), one section cloud, each consisting of 10 sections, was created by intersecting a series of 10 planes with the point cloud. The parallel planes were oriented perpendicular to the *xy* plane in a mesiodistal direction. Each single

Table 1 Fit Parameters of CEREC Crowns Fabricated Directly (Camera) and Indirectly (Scan)

Parameter	Maximum	Median	Minimum
Accuracy of alignment (root mean square)			
CEREC 3 camera, Vitablocs Mk II	0.0191	0.0152	0.0119
CEREC 3 camera, ProCAD	0.0176	0.0154	0.0117
CEREC 3 scan, Vitablocs Mk II	0.0236	0.0142	0.0109
CEREC 3 scan, ProCAD	0.0638	0.0184	0.0122
Maximum internal space (mm)			
CEREC 3 camera, Vitablocs Mk II	1.187	1.043	0.843
CEREC 3 camera, ProCAD	1.021	0.957	0.706
CEREC 3 scan, Vitablocs Mk II	1.316	0.769	0.636
CEREC 3 scan, ProCAD	1.202	0.850	0.698
Mean internal space (mm)			
CEREC 3 camera, Vitablocs Mk II	0.443	0.380	0.290
CEREC 3 camera, ProCAD	0.367	0.342	0.242
CEREC 3 scan, Vitablocs Mk II	0.494	0.279	0.214
CEREC 3 scan, ProCAD	0.442	0.302	0.227
Standard deviations of internal space (mm)			
CEREC 3 camera, Vitablocs Mk II	0.282	0.240	0.181
CEREC 3 camera, ProCAD	0.236	0.215	0.163
CEREC 3 scan, Vitablocs Mk II	0.336	0.172	0.128
CEREC 3 scan, ProCAD	0.281	0.192	0.146

plane was an *xz* plane oriented in a buccolingual direction. Points within a threshold of 0.304 µm from the intersection (neighborhood size) were included. For the best-fit registration, the optimal coordinate transformation for the alignment was computed (Surfacer). The same transformation matrix was applied to the point cloud of the replica, resulting in a movement according to the point cloud of the gypsum die. The quality assessment of the alignment was performed by root mean square (RMS).[18]

For evaluation, the shortest distance between any point of the point cloud of the replicas and the CAD surface model was calculated. The results were given by the maximum internal space and the mean internal space between the point cloud and the CAD surface model, as well as the standard deviation (SD). The statistical significance of deviations between the point clouds and the CAD surface model was analyzed with analysis of variance (ANOVA; SPSS for Windows, release 9.0, SPSS). Additionally, the 12 point clouds of one series were added to an add cloud, each consisting of about 550,000 points. The 3-D deviation between the add clouds and the CAD surface model was calculated, and the qualitative data analysis was performed.

Results

Except for one crown scanned indirectly and fabricated of ProCAD, the range of RMS was 11 to 23 µm.

The quantitative analysis of the 3-D internal fit of CEREC crowns showed that the mean internal space (Table 1) ranged from 242 to 443 µm for the crowns machined with the direct procedure and from 214 to 494 µm for the crowns machined with the indirect procedure. The maximum internal space ranged from 706 to 1,187 µm for the crowns machined with the direct procedure and from 636 to 1,316 µm for the crowns machined with the indirect procedure. The median SDs were 240 µm and 215 µm for the directly fabricated crowns of Vitablocs Mk II and ProCAD, respectively, and 172 µm and 192 µm for the indirectly fabricated crowns of Vitablocs Mk II and ProCAD, respectively. Crowns manufactured from data sets acquired indirectly (CEREC scan) showed lower means, maximums, and SDs of the internal space compared with crowns from data sets acquired directly (CEREC camera). The statistical analysis found significant differences dependent on the type of data acquisition for the maximum internal space ($P = .007$), mean internal space ($P = .042$), and SD ($P = .028$). However, no significant differences were found regarding the ceramic materials used (ANOVA, $P = .050$).

The qualitative analysis revealed that maximum deviations at the edges were not influenced by the data-acquisition procedure. The deviations at the axial surface were homogenous (Fig 2). The data sets of the 12 measurements in one series were found to be in reproducible 3-D positions.

Discussion

The hypothesis that the method for evaluation of the internal 3-D fit is suitable was accepted. Because of the methodologic objective of the study, an overall discussion of the advantages and shortcomings is required. The method is based on the registration of

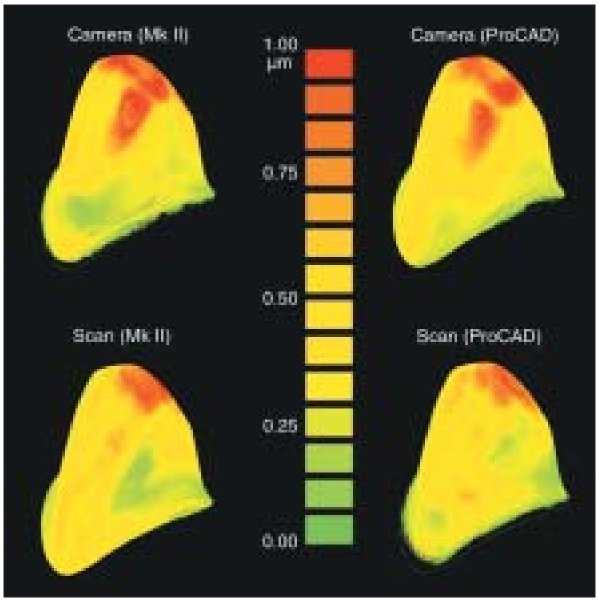

Fig 2 Qualitative analysis of 3-D internal fit of CEREC crowns fabricated directly and indirectly of Vitablocs Mk II and ProCAD.

point clouds of duplicate gypsum dies on a CAD surface model that is identical with the metal master die. Because of the computed best-fit registration of the digitized data to the CAD surface model, an identical physical positioning of the copy dies is not required.[19,20]

The assessment of the replicas directly on the metal master die (physical reference) could be performed by mechanical and optical measurement machines. Mechanical systems are limited because of the diameter of the probe used, whereas optical systems are limited because of reflections caused by shiny surfaces. The application of special powder alters the geometry so that a reliable alignment to the CAD surface model cannot be performed with the necessary high accuracy. Therefore, the assessment was performed indirectly, using one duplicate die for each crown that could be digitized with high accuracy.[13] The method protects the high-precision metal master from mechanical damage while fixing the ceramic crown on it.

Alterations of the duplicate dies compared to the metal master die and the CAD surface model are each the sum of all changes caused by each step of the process chain: *(1)* impression taking, *(2)* pouring of the duplicate dies, *(3)* digitizing, *(4)* data handling, and *(5)* registration. These alterations influence the measurements in two ways. First, the changes in the shape of the duplicate die alter the thickness of the replica compared with replicas fabricated directly on the metal master die. Second, the changes in the shape of the duplicate die alter the accuracy of the registration. However, the mean deviations of the duplicate dies of about 10 µm are of minor significance compared with the mean internal spaces of about 300 µm. Compared with alterations caused by the manufacturing of the duplicate dies, the enlargement of the replica by the application of the CEREC powder is more important. Most important for deviations are differences in the placement of the crowns on the duplicate dies caused by increased internal spaces. In summary, the measurements of the differences between the point clouds of the replicas and the respective duplicate dies were reproducible and repeatable for the crowns manufactured from different data-acquisition procedures and of different ceramics.

According to the quality scale of Peters et al,[18] the range of RMS between 11 and 23 µm is considered good. The possibility of the combined quantitative and qualitative analysis is advantageous. Using individual threshold values makes it possible to focus the evaluation on different details, for example, the location of the maximum deviation or the location of fit better than average. Nevertheless, the evaluation of the marginal fit is difficult to perform, so conventional procedures for the assessment (eg, microscopy or a conventional replica technique) might be more accurate. However, the method presented in the present study allows an assessment of the total finish line with one measurement.

Repeated measurements with the CEREC 1 device deliver pixel *z*-data within a range of ± 49 µm.[21] Pfeiffer and Schwotzer[22] found that the measurement accuracy of the CEREC 2 device in application-relevant volumes should be ± 25 µm and ± 90 µm in the full measurement range. It has to be taken into consideration that the CEREC 2 device is used for intraoral data acquisition without conventional impression techniques. Using CEREC 3, the application of conventional impression taking and extraoral digitizing leads to significantly improved fit of the crowns. This finding might be caused by the difficult conditions for intraoral data acquisition.[22]

The hypothesis that the 3-D internal fit of crowns is not influenced by the data-acquisition procedure or ceramic material used was rejected. The differences between the data-acquisition techniques were significantly different but nevertheless small when taking the absolute values as well as the clinical relevance into account. The minor influence of the data-acquisition procedure on the maximum space suggests that the manufacturing process of the crowns causes the maximum space. A variation of the spacer value,[5] which had been set to 0 µm, should have lowered the mean marginal space. Nevertheless, the maximum space was not significantly influenced by the variation of the spacer value.

Nakamura et al[16] showed considerably lower values for the mean internal gap. However, the dies used in those experiments were prepared with a flat occlusal surface. Therefore, the sophisticated machining of the internal shape of the cusps was avoided. Hence, the mismatch of the shape of the diamond tools and the surface of the prepared tooth did not lead to increased space in the incisal or occlusal areas. From the technologic point of view, that problem could be solved by the use of diamond tools with smaller diameters or decreased step width between the tool paths. Both refinements lead to increased machining times. Because of the shape of the canine, the benefit of the five-axis machining used by the CEREC 3 system is limited.

Conclusions

Within the limitations of the study, the following conclusions were drawn:

- The developed method was suitable for evaluation of the internal 3-D fit.
- Indirect data acquisition using impression taking showed improved internal fit compared with the direct procedure.
- The influence of the manufacturing process on the internal fit dominates the effect of data acquisition.
- However, the differences between the data-acquisition techniques are small compared to their absolute values.

References

1. Karlsson S. The fit of Procera titanium crowns. An in vitro and clinical study. Acta Odontol Scand 1993;51:129–134.
2. Odén A, Andersson M, Krystek-Ondracek I, Magnusson D. Five-year clinical evaluation of Procera AllCeram crowns. J Prosthet Dent 1998;80:450–456.
3. Besimo C, Jeger C, Guggenheim R. Marginal adaptation of titanium frameworks produced by CAD/CAM techniques. Int J Prosthodont 1997;10:541–546.
4. May KB, Russell MM, Razoog ME, Lang BR. Precision of fit: The Procera AllCeram crown. J Prosthet Dent 1998;80:394–404.
5. Bindl A, Mormann W. Clinical and SEM evaluation of all-ceramic chair-side CAD/CAM-generated partial crowns. Eur J Oral Sci 2003;111:163–169.
6. Martin N, Jedynakiewicz NM. Interface dimensions of CEREC-2 MOD inlays. Dent Mater 2000;16:68–74.
7. Sjögren G. Marginal and internal fit of four different types of ceramic inlays after luting. An in vitro study. Acta Odontol Scand 1995;53:24–28.
8. Kelly JR, Davis SH, Campbell SD. Nondestructive, three-dimensional internal fit mapping of fixed prostheses. J Prosthet Dent 1989;61:368–373.
9. Hewlett ER, Orro ME, Clark GT. Accuracy testing of three-dimensional digitizing systems. Dent Mater 1992;8:49–53.
10. Lee IK, DeLong R, Pintado MR, Malik R. Evaluation of factors affecting the accuracy of impressions using quantitative surface analysis. Oper Dent 1995;20:246–252.
11. Bloem TJ, Czerniawski B, Luke J, Lang BR. Determination of the accuracy of three die systems. J Prosthet Dent 1991;65:758–762.
12. Luthardt RG, Sandkuhl O, Herold V, Walter M. Accuracy of mechanical digitizing with a CAD/CAM system for fixed appliances. Int J Prosthodont 2001;14:146–151.
13. Luthardt RG, Kuhmstedt P, Walter MH. A new method for the computer aided evaluation of three-dimensional changes of dental materials. Dent Mater 2003;19:19–24.
14. Bornemann G, Lemelson S, Luthardt R. Innovative method for the analysis of the internal 3D fitting accuracy of Cerec-3 crowns. Int J Comput Dent 2002;5:177–182.
15. Wiedhahn K. The optical Cerec impression—Electronic model production. Int J Comput Dent 1998;1:41–54.
16. Nakamura T, Dei N, Kojima T, Wakabayashi K. Marginal and internal fit of Cerec 3 CAD/CAM all-ceramic crowns. Int J Prosthodont 2003;16:244–248.
17. Schreiber W, Notni G, Kuhmstedt P, Gerber J, Kowarschik R. Optical 3D coordinate measuring system using structured light. In: Gorecki C (ed). Proceedings of SPIE 1996: Optical Inspection and Micro-measurements, 10–14 June, Besançon, France. Bellingham, WA: International Society for Optical Engineering, 1996:620–627.
18. Peters MC, Delong R, Pintado MR, Pallesen U, Qvist V, Douglas WH. Comparison of two measurement techniques for clinical wear. J Dent 1999;27:479–485.
19. Mehl A, Gloger W, Kunzelmann KH, Hickel R. A new optical 3-D device for the detection of wear. J Dent Res 1997;76:1799–1807.
20. Yamashita S, Ai M, Geng Q, Sato M, Shinoda H, Ando S. Application of a newly developed 3-D deformation measurement system to prosthetic dentistry. J Oral Rehabil 1996;23:849–855.
21. Benz C, Schwarz P. How precise is the optical Cerec impression [in German]? Dtsch Zahnarztl Z 1991;46:632–634.
22. Pfeiffer J, Schwotzer A. Three dimensional optical measurement of teeth [in German]. Technisches Messen 1996;63:254–261.