Optical Three-Dimensional Scanning Acquisition of the Position of Osseointegrated Implants: An in vitro Study to Determine Method Accuracy and Operational Feasibility

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ABSTRACT

Purpose: Manufacturing complex prosthetic framework on osseointegrated implants requires precision at every step of execution. The purpose of this study was to verify the possibility of applying the technology of image acquisition to determine the spatial position of osseointegrated implants.

Materials and Methods: An optical three-dimensional scanning technique was employed: its measurement systematic error (bias) was calculated by comparing the results with the detection on a coordinates measuring machine. Measurements were carried out on master casts by doing an in vitro simulation of intraoral conditions.

Result: This study showed that the bias error value of the three-dimensional optical acquiring system was situated between 14 and 21 μm.

Conclusion: As far as the accuracy is concerned, it seems possible to use the three-dimensional image acquisition technology as a valid alternative to traditional impression-making procedures. However, the bias levels obtained in this in vitro study will have to be confirmed in a clinical trial.

KEY WORDS: bias, dental implants, fringe patterns light, optical measurements, structured light

INTRODUCTION

Manufacturing complex prosthetic framework on multiple osseointegrated implants requires accuracy at every step of execution. The impression making, the development of master cast, the waxing, the milling, and the finishing of the framework cannot be standardized. Each of these steps is subject to different degrees of error that can add up to generate an imprecise fit between the components of the whole prosthesis.[1] Jemt and Lie[2–4] demonstrated that the greater amount of the total error is due to the framework cast procedure: the value of this error may reach up to 150 μm. A clinically nonpassive fit between the prosthesis and supporting structures, when screwed onto the implants, creates stresses, which may lead to undesirable side effects on the peri-implant bone[5–7] or screw ruptures.[8,9]

Industrial titanium milling techniques, associated with CAD/CAM technology, have shown that these

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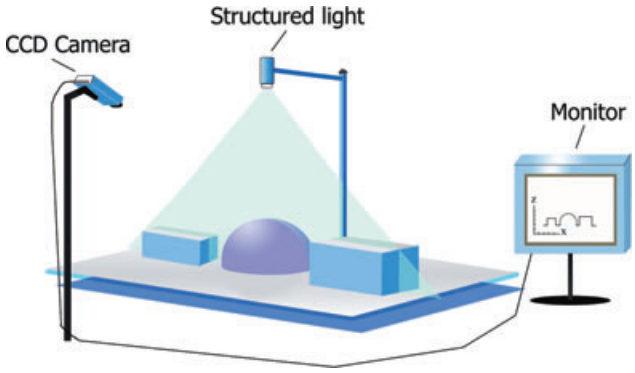

Figure 1 Working scheme of an active range camera.

methods can be applied to the manufacturing of titanium prosthetic frameworks, which are lighter than traditional gold alloys, with consequent reduction of material costs and increased biocompatibility.[10–12] This procedure is prone to errors when determining the position of implant supporting surfaces and the consequent prosthetic fit to these surfaces. This fact prompts the search for an alternative system to replace the development of the master cast. The three-dimensional image acquisition may be the most suitable and effective method to achieve this goal. An application of this technique is already performed using the photogrammetric method:[13–17] the image is acquired with reflex cameras to which film-stretching devices have been adapted. Reflecting mirrors placed at the objective sides are used in some cases. Images are digitally elaborated by high-resolution scanners, which acquire shape and colors directly from film.

Nowadays, the development of digital three-dimensional scanning systems offers new possibilities for optical acquisition of implant position. For this goal, the most suitable three-dimensional digital scanner was one which uses the "fringe patterns light projection." This kind of device belongs to the structured light (active range camera) systems family; it is made of a light source coupled with an image-shooting device (usually a camera). A definite angle regulates the position both of the source and the camera. The light source hits the object with fringes of light that are shot by the camera, whose angled position enables the surface profile to be enhanced by the original ray of light (Figure 1). A thicker object will show, accordingly, heavier bending lines. By projecting many fringes and moving them along the whole surface to be detected, a complete scan of the object, and accordingly, its three-dimensional rebuilding, can be obtained. This system can provide high performances in accuracy, field of view, and scanning speed, better than other optical scanning systems. This is why three-dimensional fringe light scanners are widely used today in geoengineering, architecture, medicine,[18] mechanics, and preservation and restoration of cultural heritage.

The purpose of this study was to confirm the technical feasibility and the potential for using a three-dimensional fringe light optical acquisition in implant-supported prosthetic practice, and to define the position of endosseous implants on models before a clinical trial. To achieve this goal, it was necessary to evaluate the bias (or systematic error) of the three-dimensional scanning measurement procedure.

MATERIALS AND METHODS

The bias value represents the sum of different elements: measurement device accuracy, operator ability, measuring procedure, human observation, and others. Every measurement process is affected by bias, and consequently, the true value of the measurement is systematically overstated or understated. So, the bias must be known in order to confirm or refuse the suitability of any measurement process.

In this study, the bias was evaluated by determining the difference between the reference value (detected through coordinates measuring machine [CMM] measurements) of each measurement and the corresponding value provided by the three-dimensional scanner. The CMM was used as a reference measurement system because of its very high metrologic performances (the accuracy value determined by calibration was 0.04 μm).

The study was performed by using two master casts from two clinical cases having five implant analogues each (3i Implant Innovations, West Palm Beach, FL, USA), supporting ceramic reference markers (Figure 2A). A series of reference markers, made of white opaque ceramic, were assembled on a stainless steel-type AISI-310 base referencing the implant position. An optoelectronic device employing fringe patterns light, type Steinbichler COMET VZ250, with a declared accuracy between 20 and 40 μm, a field of view of 200×150 mm, and a CCD sensor resolution of $1{,}600 \times 1{,}200$ pixels (Steinbichler Optotechnik GmbH, Neubeuern, Germany) (Figure 2, B and C) was used. The optical device was connected to a PC unit provided with dedicated software, Steinbichler COMETplus

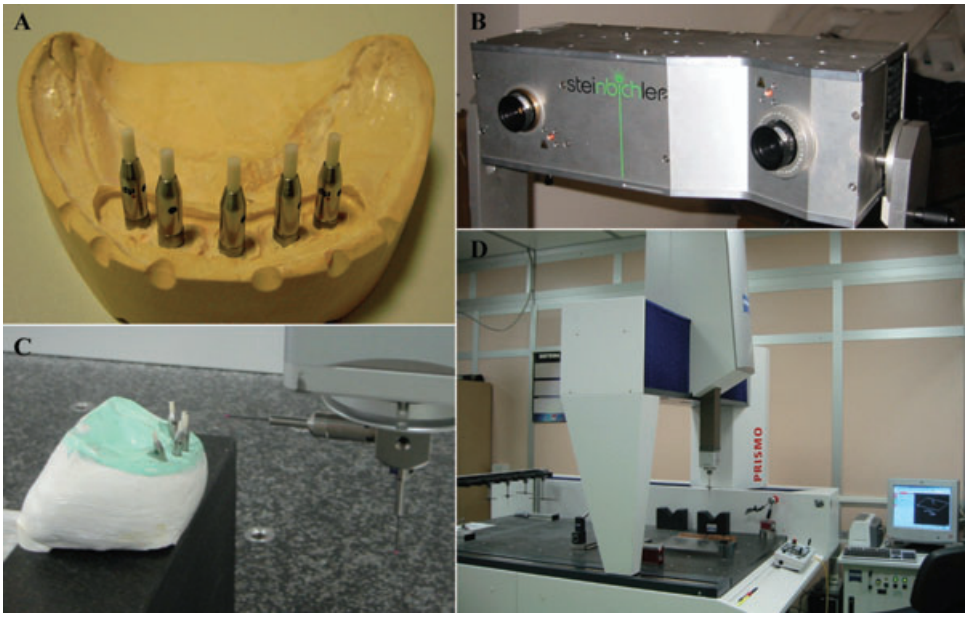

Figure 2 The two master casts support the reference ceramic markers (A, model 2). They are analyzed using a fringe patterns light optical device Steinbichler VZ250 (B and C, model 1) and a Carl Zeiss coordinates measuring machine (D).

BASIC and COMETplus MATCH, to elaborate the acquired point cloud and to retrieve the three-dimensional image of the object (Steinbichler Optotechnik GmbH). A CMM provided the contact probe to scan the object. This CMM, connected to a PC unit with software dedicated to three-dimensional images elaboration and space coordinates detection (Zeiss Prismo-7 + CALYPSO, Carl Zeiss, Oberkochen, Germany) (Figure 2D), was used to determine the true value of each measurement acquired by the three-dimensional scanner. A roundness measuring machine, TELYROND 262, was used to detect marker dimensions, and was connected to a PC unit provided with software dedicated to data interpretation and control reports emission (Taylor Hobson Limited, Leicester, England).

The research consisted of four metrologic phases.

1. All markers were investigated to certify the metrologic dimensions required by the international ISO 1101:1983 standard (technical drawings, geometrical tolerancing). In particular, the following characteristics were tested for each marker: diameter, circularity, coaxiality, perpendicularity, flatness of reference surface, and total height.
2. The reference values of the spatial position of the markers screwed onto implant analogues were detected through CMM measurements for each cast. Space coordinates were determined by taking the middle-positioned implant as a reference and by fixing the point 0 as the top center of the equivalent marker.
3. The space positions of the markers (the same as for step 2) were subsequently detected by fringe patterns light three-dimensional scanner. During the optical scanning procedure, different acquiring modalities were tested to determine an adequate operative procedure (Figure 2C) simulating the intraoral scanning conditions.
4. The last phase concerned the determination of the bias of the three-dimensional scanning procedure by calculating the differences between the measurements obtained using this method and the reference values given by the CMM system (ISO 10360-4:2000, about geometrical product specifications, acceptance, and reverification tests for CMM).

To determine the bias, data associated with the following dimensions were examined:

- markers diameter;
- space coordinates referred to X, Y, and Z axis related to the top center of each marker;
- polar distances among the top centers of each marker; and
- angle vectors as the expression of the marker axis inclination compared with reference marker axis (middle-positioned implant).

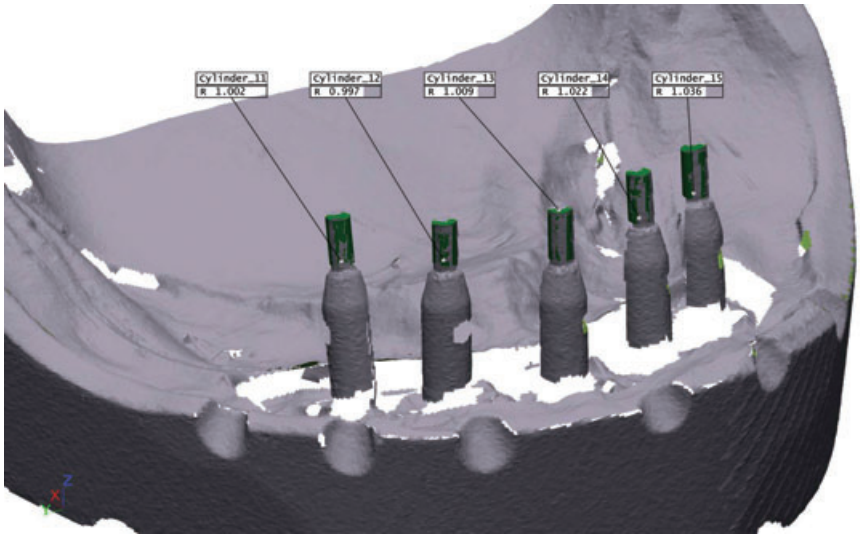

Figure 3 Diameter measurements with three-dimensional scan.

In total, 38 scannings were carried out from which nine three-dimensional models were reconstructed. A total of 225 measurements were collected, categorized as follows:

- markers diameter – 10 measurements;
- space coordinates (X, Y, and Z) – 45 measurements;
- polar distances – 90 measurements; and
- angle vectors – 90 measurements (45 of X-Z angle, and 45 of Y-Z angle).

Before each measurement series was carried out with both CMM and three-dimensional scanning modality, a calibration procedure was performed to confirm the metrologic measurement validity. The calibration showed that the three-dimensional scanner accuracy was less than 20 μm.

RESULTS

The results of this study show the degree of bias of three-dimensional scanning measurements when compared with the reference values resulting from the CMM system measurement. The bias is expressed as the difference between the observed average measurements and the reference average (establishing the reference average is best determined by measuring with the most accurate measuring equipment available).

Detections on markers diameters (Figure 3) allowed the determination of a bias of 18.5 μm (Table 1). The bias value related to the detections on space coordinates (Figure 4), referred to as X, Y, and Z axis, proved to be 15.5 μm (Table 2). The bias of the polar distances (Figure 5) was 14.2 μm (Table 3). The results analysis referred to differences along lying planes of angle vectors (Figure 6) showed a bias value near 0.08°, while the standard deviation of the differences was around 0.20°. Assuming a marker standard height value of 15.00 mm, the projection error at the marker bottom (caused by a difference of the angle vector of 0.08°) was about 21 μm (Table 4).

The final result demonstrated that, independent of the dimension being considered, the bias error value of the three-dimensional light fringe system was situated between 14 and 21 μm. This result confirmed the calibration data obtained before each scanning procedure.

TABLE 1 Bias Error Measured on Marker Diameters (Referred in Millimeters)

Position	Coordinates Measuring Machine (Reference)	Optical Scanning Average	Bias
1	1.99315	2.0120	0.018850
2	1.99445	1.99422	−0.000228
3	1.99700	2.01578	0.018778
4	1.99410	2.01133	0.017233
5	1.99545	2.01489	0.019439
		Average	0.014814
		Bias	0.0185

Average values from optical scannings are calculated from the measurements on the nine three-dimensional models.

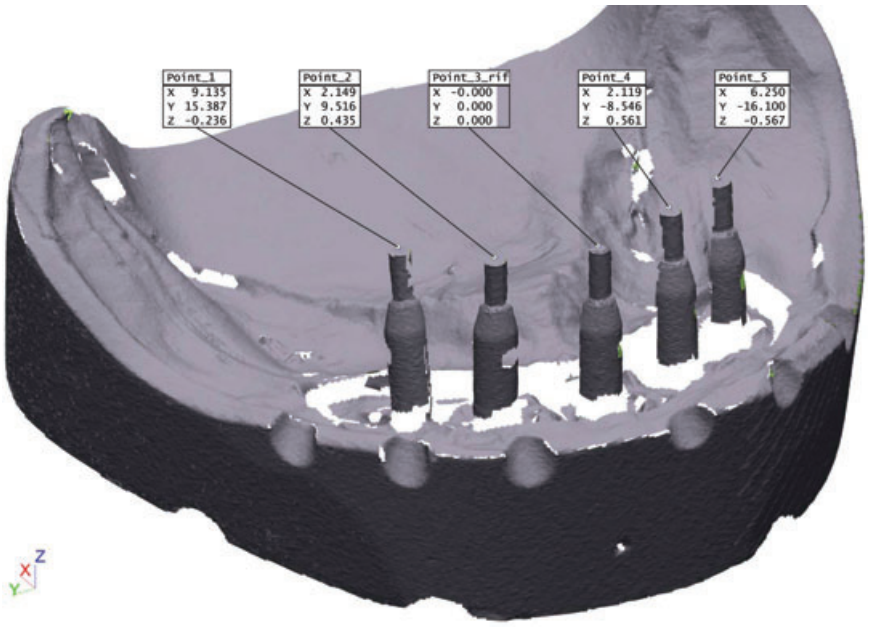

Figure 4 Implant position coordinates (X, Y, and Z) with three-dimensional scan.

DISCUSSION

The whole prosthesis manufacturing process is difficult to verify and to certify, as it depends on traditional clinical and laboratory techniques for some steps – like impression-making procedures[19,20] and master cast developing procedures – which are difficult to standardize in terms of materials and execution.

The introduction of CAD/CAM elaboration of scanned premade resin structures and the subsequent manufacturing of titanium industrially milled frameworks show the efforts to overcome the above-mentioned problems linked to dimensional changes in casting procedures.[10,11] In these cases, the entire manufacturing process begins with the correct impression procedure and depends on the accuracy of the master cast.

The solution to the problem could be to determine the spatial implant position through digital technologies, and to send the framework milling mathematics to a CAD/CAM system.[21] By eliminating the possibility of using contact probes in the oral cavity, it may be possible to imagine the development of optical acquiring systems

TABLE 2 Expression of Bias Error Referred to Space Coordinates X, Y, and Z

Coordinates Measuring Machine (Reference)			Optical Scanning Average			Differences		
X	Y	Z	X	Y	Z	X	Y	Z
−15.4018	9.1565	−0.1843	−15.3957	9.1490	−0.2043	0.0061333	−0.0075	−0.0200333
−9.5335	2.119	0.4399	−9.5163	2.1270	0.4720	0.0171667	0.008	0.0321
0	0	0	0	0	0	0	0	0
8.5778	2.119	0.5252	8.5607	2.1200	0.5013	−0.01713	0.001	−0.0239
16.0998	6.2492	−0.5727	16.0900	6.2440	−0.6333	−0.00980	−0.0052	−0.0606333
					Average	−0.00091	−0.00092	−0.01811
					Standard deviation	0.01548	0.00695	0.03815
							Bias	0.0155

Cast 1 (dimensions in millimeters). Test conditions: 4 acquisitions × 150° field of view (–75°, –25°, +25°, +75°). In this table, average values from optical scannings are calculated from the measurements on three three-dimensional models (tests 3, 6, and 7).

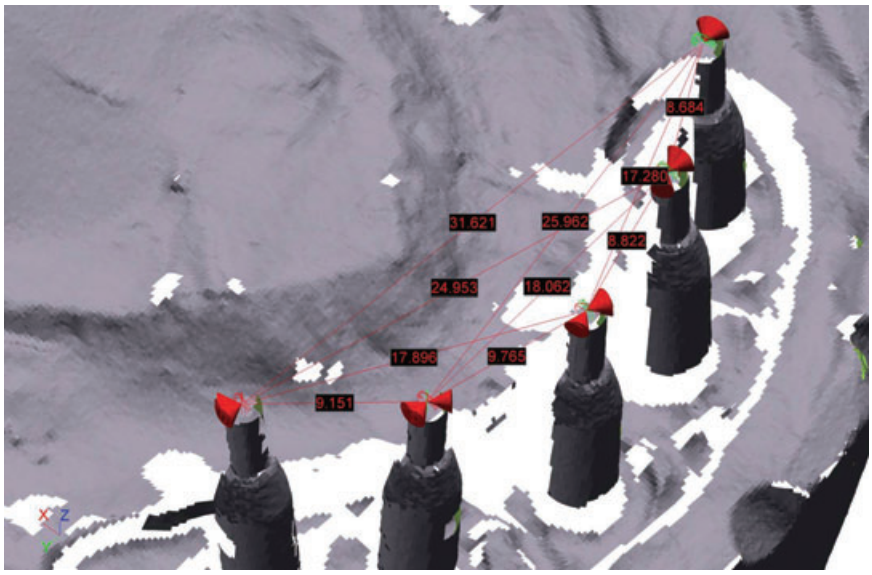

Figure 5 Polar distance measurements with three-dimensional scan.

to rebuild a digital solid model of the clinical situation, and to transfer to a CAD-CAM production software the coordinates necessary to build prosthetic structures with a standardized accuracy. The results of the present study confirm the real possibility, as far as dimensional error is concerned, to employ a three-dimensional fringe light scanning as a first step of the manufacturing process.

The in vitro simulation of an existing intraoral condition has shown that the number of scans taken is much more important than the device angle referred to the object taken into consideration. This is because images acquired by the three-dimensional scanning need to be processed by a software furnished with a "best-fitting function," which recognizes and geometrically rebuilds the object from the scanning point cloud; the more data provided, the better. For optimum acquisition, it seems more important to perform a large quantity of fast scannings than to do a small quantity of high-definition scannings.

TABLE 3 Bias Error Referred to Polar Distances

Distance	Coordinates Measuring Machine (Reference)	Optical Scanning Average	Difference
Marker 1–2	9.1843	9.183333	–0.0010
Marker 1–3	17.919	17.91033	–0.0087
Marker 1–4	25.001	24.97667	–0.0243
Marker 1–5	31.6378	31.622	–0.0158
Marker 2–3	9.7761	9.762333	–0.0138
Marker 2–4	18.1116	18.077	–0.0346
Marker 2–5	25.9837	25.95867	–0.0250
Marker 3–4	8.8513	8.833667	–0.0176
Marker 3–5	17.2796	17.27067	–0.0089
Marker 4–5	8.6512	8.659333	0.0081
		Average	–0.0142
		Bias	0.0124

Cast 1 (dimensions in millimeters). Test conditions: 4 acquisitions × 150° field of view (–75°, –25°, +25°, +75°). In this table, average values from optical scannings are calculated from the measurements on three three-dimensional models (tests 3, 6, and 7).

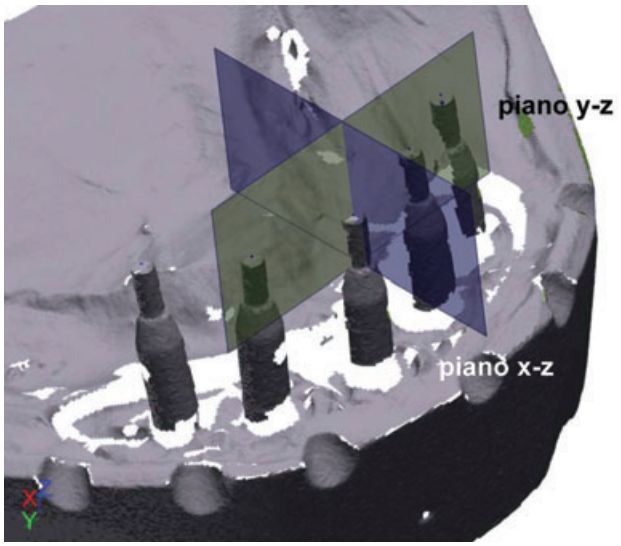

Figure 6 Angular vector measurements with three-dimensional scan.

The selected optical measurement system must consider the acquisition speed combined with a good optical and electronic component resolution. The authors consider the devices provided with a CCD of at least 1,200 × 1,000 pixels and a field of view of not over 100 × 80 mm to be adequate. To ensure acquisition process repeatability, it is necessary, once the optical device type has been selected, to accurately define the marker shape and the construction material. In fact, the quality of digitized surface reconstruction, and consequently, the measurement variations are shape-dependent, whereas the kind of material affects the quantity of points acquired. Defining these variables is the premise for standardizing acquisition procedures.

The quantity of measurements (225 in total) performed using the three-dimensional scanner represents a suitable sample size to determine the bias error of the scanning procedure. For clinical purposes, the authors think it is necessary to recalculate the bias error with data collected in an in vivo study, because the morphology and behavior of patients may significantly affect the measurement results. Furthermore, the comparison between the error because of the traditional impression procedure (100–150 µm) and the error related to the three-dimensional scanning (less than 25 µm) demonstrated that this second method may effectively reduce the error in the overall manufacturing process, even if the in vivo three-dimensional scanning was to be affected by negative conditions.

CONCLUSION

The bias value obtained in this study is promising for imaging-acquiring technology as an alternative to traditional impression techniques, which are difficult to standardize because of errors related to impression-making phases and master cast development.

A follow-up of this study should include marker standardization (physical and morphological characteristics). Other goals are to identify a suitable optical acquiring system, to define standardized operational procedures for the acquisition process, and to elaborate computerized information to be sent to the milling machine.

TABLE 4 Bias Error Referred to Angle Vectors

	Coordinates Measuring Machine (Reference)		Optical Scanning Average		Difference	
Position	X-Z	Y-Z	X-Z	Y-Z	X-Z	Y-Z
1	–2.01	5.84	–1.973	5.800	0.037	–0.040
2	–0.29	–1.02	–0.417	–0.623	–0.127	0.397
3	0	0	0	0	0	0
4	–0.78	2.12	–0.940	2.100	–0.160	–0.020
5	–0.26	2.18	–0.323	2.133	–0.063	–0.047
			Average		–0.0783	0.0725
			Standard deviation		0.08652	0.21641
					Bias	0.08

Cast 1 (dimensions in degrees). Test conditions: 4 acquisitions × 150° field of view (–75°, –25°, +25°, +75°). In this table, average values from optical scannings are calculated from the measurements on three three-dimensional models (tests 3, 6, and 7).

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REFERENCES

1. Carr AB, Stewart RB. Full-arch implant framework casting accuracy: preliminary in vitro observation for in vivo testing. J Prosthodont 1993; 2:2–8.
2. Jemt T, Lie A. Accuracy of implant-supported prostheses in the edentulous jaw: analysis of precision of fit between cast gold-alloy frameworks and master casts by means of a three-dimensional photogrammetric technique. Clin Oral Implants Res 1995; 6:172–180.
3. Jemt T. Three-dimensional distortion of gold alloy castings and welded titanium frameworks. Measurements of the precision of fit between completed implant prostheses and the master casts in routine edentulous situations. J Oral Rehabil 1995; 22:557–564.
4. Lie A, Jemt T. Photogrammetric measurements of implant positions. Description of a technique to determine the fit between implants and superstructures. Clin Oral Implants Res 1994; 5:30–36.
5. Jemt T, Lekholm U. Measurements of bone and framework deformations induced by misfit of implant superstructures. A pilot study in rabbits. Clin Oral Implants Res 1998; 9:272–280.
6. Jemt T, Book K. Prosthesis misfit and marginal bone loss in edentulous implant patients. Int J Oral Maxillofac Implants 1996; 11:620–625.
7. Jemt T, Lekholm U, Johansson CB. Bone response to implant-supported frameworks with differing degrees of misfit preload: in vivo study in rabbits. Clin Implant Dent Relat Res 2000; 2:129–137.
8. Kallus T, Bessing C. Loose gold screws frequently occur in full-arch fixed prostheses supported by osseointegrated implants after 5 years. Int J Oral Maxillofac Implants 1994; 9:169–178.
9. al-Turki LE, Chai J, Lautenschlager EP, Hutten MC. Changes in prosthetic screw stability because of misfit of implant-supported prostheses. Int J Prosthodont 2002; 15:38–42.
10. Jemt T, Back T, Petersson A. CNC-milled titanium frameworks for implant treatment in the edentulous jaw. Int J Prosthodont 1999; 12:209–215.
11. Ortorp A, Jemt T. Clinical experiences of CNC-milled titanium frameworks supported by implants in the edentulous jaw: 1-year prospective study. Clin Implant Dent Relat Res 2000; 2:2–9.
12. Ortorp A, Jemt T. Clinical experience of CNC-milled titanium frameworks supported by implants in the edentulous jaw: a 3-year interim report. Clin Implant Dent Relat Res 2002; 4:104–109.
13. Jemt T, Back T, Petersson A. Photogrammetry–an alternative to conventional impressions in implant dentistry? A clinical pilot study. Int J Prosthodont 1999; 12:363–368.
14. Jemt T, Book K, Lie A, Borjesson T. Mucosal topography around implants in edentulous upper jaws. Photogrammetric three-dimensional measurements of the effect of replacement of a removable prosthesis with a fixed prosthesis. Clin Oral Implants Res 1994; 5:220–228.
15. Jemt T, Rubenstein JE, Carlsson L, Lang BR. Measuring fit at the implant prosthodontic interface. J Prosthet Dent 1996; 75:314–325.
16. Jemt T. In vivo measurements of precision of fit involving implant-supported prostheses in the edentulous jaw. Int J Oral Maxillofac Implants 1996; 11:151–158.
17. Ortorp A, Jemt T, Back T. Photogrammetry and conventional impressions for recording implant positions: a comparative laboratory study. Clin Implant Dent Relat Res 2005; 7:43–50.
18. Chen LH, Tsutsumi S, Iizuka TA. CAD/CAM technique for fabricating facial prostheses: a preliminary report. Int J Prosthodont 1997; 10:467–472.
19. Carr AB. Comparison of impression techniques for a five-implant mandibular model. Int J Oral Maxillofac Implants 1991; 6:448–455.
20. Carr AB, Master J. The accuracy of implant verification casts compared with casts produced from a rigid transfer coping technique. J Prosthodont 1996; 5:248–252.
21. Grossmann Y, Pasciuta M, Finger IM. A novel technique using a coded healing abutment for the fabrication of a CAD/CAM titanium abutment for an implant-supported restoration. J Prosthet Dent 2006; 95:258–261.