JOURNAL OF PROSTHODONTIC RESEARCH XXX (2016) XXX–XXX

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journal homepage: www.elsevier.com/locate/jpor

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Original article

Comparison of the accuracy of direct and indirect three-dimensional digitizing processes for CAD/CAM systems – An in vitro study

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ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form
16 June 2016
Accepted 6 July 2016
Available online xxx

Keywords:
Digital impression
Intraoral scanner
Accuracy
CAD/CAM method

ABSTRACT

Purpose: To compare the accuracy (trueness, precision) of direct and indirect scanning CAD/CAM methods.
Methods: A master cast with prepared abutments and edentulous parts was created from polymethyl methacrylate (PMMA). A high-resolution industrial scanner was used to create a reference model. Polyvinyl-siloxane (PVS) impressions and digital impressions with three intraoral scanners (iTero, Cerec, Trios) were made ($n = 10$ for each) from the PMMA model. A laboratory scanner (Scan CS2) was used to digitize the sectioned cast made from the PVS impressions. The stereolithographic (STL) files of the impressions ($n = 40$) were exported. Each file was compared to the reference using Geomagic Verify software. Six points were assigned to enable virtual calliper measurement of three distances of varying size within the arch. Methods were compared using interquartile range regression and equality-of-variance tests for precision, and mixed-effects linear regression for trueness.
Results: The mean (SD) deviation of short distance measurements from the reference value was −40.3 (79.7) μm using the indirect, and 22.3 (40.0) μm using the direct method. For the medium distance, indirect measurements deviated by 5.2 (SD: 111.3) μm, and direct measurements by 115.8 (SD: 50.7) μm, on average; for the long distance, the corresponding estimates were −325.8 (SD: 134.1) μm with the indirect, and −163.5 (SD: 145.5) μm with the direct method. Significant differences were found between the two methods ($p < 0.05$).
Conclusions: With both methods, the shorter the distance, the more accurate results were achieved. Virtual models obtained by digital impressions can be more accurate than their conventional counterparts.

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http://dx.doi.org/10.1016/j.jpor.2016.07.001
1883-1958/

1. Introduction

Technical innovations in the digital world have more influence on dentistry each year. Nowadays patients' records and X-rays are made digitally [1]; digital devices help determine tooth colour [2] and registration of the correct occlusal position [3]. Digital dental technology (DDT) tries to provide quicker and more comfortable solutions than conventional methods. At the same time, it promises more accurate results which may have a vast impact on dental work. Moreover, DDT may be more cost and time effective [4–7] and also seems to be preferred by dental students, whose choices will determine what impression techniques are most commonly used in the future [7,8]. When it comes to making indirect dental restorations, it is necessary to send all the true information about a patient's oral cavity to the dental laboratory. Conventionally this has been done by impressions. The more accurate the impression, the more accurate will the restoration be [9,10]. Starting in the 1980s, digitizing the impression procedure and computer aided design and computer aided manufacturing (CAD/CAM) technology was introduced to dentistry [5,9–12]. CAD/CAM is one of the most dynamically developing areas in dentistry. Nowadays there are two possible methods to the digital workflow and for using the CAD/CAM system to create dental restorations digitally: the direct and the indirect approaches [13]. Conventionally, the workflow starts with a laboratory scanning of the stone cast after impression taking; this is the indirect approach. Today it is also possible to digitize the information about the oral cavity directly. With the direct method, a scan is made of the oral cavity by an intra-oral optical scanner. The dental restoration is designed with the computer (CAD), then a computer-controlled fabricating machine (CAM) starts to mill the restoration from the chosen material [14].

More and more innovations these days tend to rely on the direct method of imaging, which translates to a rapid development of intraoral scanners. From working with relatively older systems which used a thin coat of opaque powder on the scanning surface, dentistry has moved on to newer, powder-less, wet scanning systems, which can also reach the posterior regions that are more challenging to scan [15]. Initially, only shorter parts of an arch were technically possible to digitize; however, full arch scans are also available these days [16,17]. Direct digitization of edentulous jaws is not recommended because poorly differentiated structures are difficult to capture with optical scanners [18].

The accuracy of dental work also depends on the laboratory process, [19] and technicians may need a physical cast during selected steps of the digital workflow. There are studies which evaluate the accuracy of dies prepared from digital impressions in comparison to that of stone models. They invariably find digital impression systems to be sufficiently accurate for clinical application, but advise to consider their limitations and use them with caution [19–22].

In this study, measurement accuracy is interpreted in line with the concepts outlined in ISO standard number 5725 [23]. The standard describes the accuracy of measurements as having two components, trueness and precision: trueness defines the extent to which the measurements deviate from the true size of the object, and precision shows the fluctuation of the measured results. Practically, these are often measurement method and technique sensitive.

The aim of the study was to evaluate and compare the accuracy (trueness and precision) of the two available CAD/CAM approaches (indirect and direct) by comparing scans made off the same model using different direct (iTero, Trios, Cerec Omnicam) and indirect (Straumann® CARES® Scan CS2, Institut Straumann AG, Basel, Switzerland) digital impression systems.

2. Materials and methods

2.1. *Reference model*

A PMMA maxillary master cast (Fig. 1) was created with four full crown preparations with a shoulder finishing line and used as a reference model (prepared first premolars, left central incisor and left second molar). The PMMA model had a unilateral and an anterior bounded edentulous area with the absence of the central and lateral incisors on the right hand side and of the second premolar and first molar on the left hand side. Edentulous alveolar crests contain a reduced number of reference points for optical scanners; the aim was to see if this was associated with virtual model distortion. Edentulous arches lack clearly remarkable points which are essential for scanners to achieve correct stitching [18]. In addition to edentulous spaces, the distance between abutments also negatively affects the recognition of overlapping areas and, consequently, the stitching process and the accuracy of the digital impression [24].

2.2. *Reference scanner*

The reference scanner used in this study was a point-laser scanner connected to a CNC milling device (TwoCam 3D, SCAN technology A/S; Ringsted, Denmark). The scanner uses 635 nm laser light (1 mW power, Class IEC 2). It has a known distortion for a given range; the one for the 200 mm range was used. The system can detect 0.1 mm objects with a known accuracy of $\pm$0.025 mm. The principle of operation is that of a double triangulating point scanner.

2.3. *Direct CAD/CAM method*

To investigate the direct approach, digital optical impressions were made of the study model with three different digital impression scanner systems: iTero (Align Technology B.V., Amsterdam, Netherlands), Trios (3Shape Headquarters, Copenhagen, Denmark) and CEREC Omnicam (Sirona Dental GmbH, Salzburg, Austria). All three systems are able to take full-arch impressions without using the outdated powder-based technique. Ten digital impressions were made using each system, and the scanned data were exported in STL format. One experienced investigator, familiar with all the scanning devices, performed the scans.

2.3.1. *Scanning devices and strategies*

2.3.1.1. *iTero*. The iTero system uses parallel confocal imaging technology to record intraoral still images of the dental

Fig. 1 – The polyurethane reference model with four complete crown preparations.

arch without the use of powder and stitch them together to get a colour 3D digital impression, which can exported as an STL file for further processing in the CAD/CAM workflow [14,25].

The scan was started with the prepared teeth. Five images were made of each tooth: from the occlusal, buccal, oral, mesial, and distal surfaces. When a critical lack of data was detected, the system prompted for additional scans. After the prepared teeth, the scanning process continued with the other teeth in the arch. The system requested an oral and vestibular image about the non-prepared teeth in a 45° view angle from the occlusal surface. Finally, the software matched all the scans into one full arch. The datasets were sent to the company to cut out the unnecessary scan information, a process called ''data cleaning'' [9,11].

2.3.2. *Trios*

The scanner is also a powder-free, still-image camera that takes image series about the surfaces. However, its camera records the still images at such a high rate that it is quite indistinguishable from working with a video camera – the system is based on ultrafast optical scanning technology [14,25].

Manufacturer's instructions were followed for each scan: the occlusal surface of the full arch was scanned with constant movement starting at the last tooth on the right hand side. Upon reaching the end of the other side, the head was rotated 45° to scan the palatal surfaces. After rotating the scanner head 45° in the opposite direction, the buccal surfaces were scanned the same way. Finally, the software rendered the virtual model. Additional scan need was indicated on the virtual model if the lack of data was substantial.

2.3.3. *Cerec OmniCam*

Cerec OmniCam is a recently introduced intraoral scanner type that uses video recording technology. It has a live colour stream, therefore it is capable of continuous data capture. Video is captured as the digital camera is moved around the teeth producing a full-colour digital cast, also without powder [14,25].

Data capturing started in the molar region with the occlusal surfaces. Eventually, the full arch was scanned by rotating the camera around each tooth to buccal and oral perspectives. When reaching the front region, the labial surfaces of the incisors were first scanned starting at the premolars, then back to the premolars and continuing with the previous technique. The prepared teeth were scanned with a mesio-distal waving movement, rotating the camera to both buccal and palatal perspectives. At the end of the rotation, the camera head was parallel with the vertical surface of the tooth. The real-time display enabled immediate correction at inaccurate areas without interrupting the scanning process [9,11].

2.4. *Indirect CAD/CAM method*

Ten 1-step putty/light-body impressions were made with polyvinyl siloxanes (PVS) material (Elite HD+ Maxi Putty Soft Normal, Elite HD+ Light Body Normal, Zhermack® SpA, Rovigo, Italy) according to manufacturer's recommendations with a stock perforated metal tray (Medesy 6000). PVS are one of the most commonly used impression materials in restorative dentistry; they are proven to be able to provide accurate information about the oral cavity for almost all types of indirect restorations [26]. The 1-stage (simultaneous) technique was chosen due to its common usage in clinical practice [27,28]. Studies show that 2-step impression techniques can have higher discrepancies compared to the single-step impression technique [29]. Single-step also takes a shorter chair-time than the two-stage approach, which translates to increased patient comfort and acceptance [30]; these properties make it better suited for comparison with the cost- and time-efficient direct digital impression technique. Studies show that the one-step technique has clinically acceptable accuracy [31].

The manufacturer's recommended polymerization times were doubled to compensate for the impressions not being made at mouth temperature. We used a universal tray adhesive as recommended by the manufacturer; however, it is not necessary with perforated metal trays [27].

One investigator automixed all putty preparations while another investigator injected the light-body impression material around the prepared teeth. The teeth were completely syringed in order to maximize the required precision [32]. Light-body material was also injected onto the tray filled with putty. The same investigator then seated the tray on the PMMA model.

All impressions were transported to the dental technician's laboratory within half an hour to cast the impressions within 2 h [31]. Ten casts were made using type-IV stone material (GC Fujirock EP, GC Corp., Tokyo, Japan). Distilled water was used for stone mixing, in accordance with manufacturer's instructions. The mixing was carried out in a ratio of 100 g to 25 ml water, initially by hand to incorporate the water, and then mechanically under vacuum for 20 s (BEGO Motova SL, BEGO USA, Lincoln, RI). The impressions were poured with the aid of a mechanical vibrator (WASSERMANN Rüttler KV-26, Wassermann Dental-Maschinen GmbH, Hamburg, Germany)

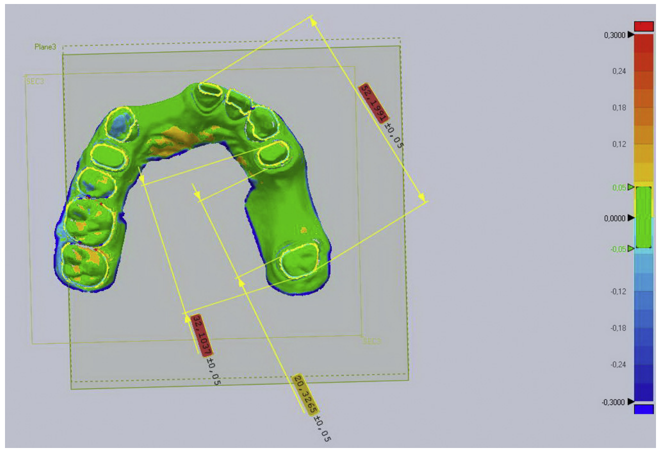

Fig. 2 – Colour coded deviation view of the superimposition, and digital calliper measurements of the three different distances.

operating at 6000 cycles/min and at an amplitude of 0.4 mm, according to manufacturer's instructions. The stone casts were allowed to set for 1 h and then removed from the impressions and trimmed. Saw-cut models were fabricated with the Giroform system (Amann Girrbach Dental, Pforzheim, Germany) [32]. In at least 12 h (but not more than 72 h) after pouring, all models were captured using a laboratory scanner (Straumann CARES Scan CS2 Visual 8.0 software, Institut Straumann AG, Basel, Switzerland) and all gathered data were exported in STL file format.

2.5. *Superimposition and digital calliper*

For comparison of the digital data, the Geomagic verify software (3Dsystems, 333 Three D Systems Circle, Rock Hill, USA) was used, which evaluates the STL files of the direct and indirect CAD/CAM methods against the reference STL file using the best fit alignment algorithm.

Some studies measure the whole deviation, others use surface points, and some others use linear distance measurements [33]. In this study distances were measured because that is how best to detect torsions of the arch. The optical impressions' weakest point was in "stitching" the images together to capture the whole arch – a slight displacement or rotation of a few images can result in an inaccurate dental arch on the opposite side.

Superimposition (placement of direct/indirect scan on top of reference scan) and digital calliper (tool to measure distances on each virtual cast between predefined reference points) are built in features of that software.

To pick the reference points on 3D scan data, first a plane which intersected each tooth was defined, next the mesio-distal diameters of the prepared teeth (24, 27, 21) were determined.

Measuring direction was defined between 21 mesial point-27 distal point; 24 mesial point-27 distal point and 24 distal point-27 mesial point. This function enabled the measurement of three different distances in the arch (Fig. 2): short distance (24–27 inside), medium distance (24–27 outside), and long distance (21–27 left side).

2.6. *Statistical methods*

Deviation measurement data were described using means, standard deviations, and interquartile ranges for each CAD/CAM method. Differences between methods in precision were assessed by comparing measurement data interquartile ranges using interquartile range regression, and comparing variances using Levene's original robust test for the equality of variances and also its median-based variation (as proposed by Brown and Forsythe). Between-groups differences of means were evaluated using mixed-effects linear regression allowing for a heterogeneity in group-level variance of residuals, and were interpreted as indicating differences between methods in measurement trueness. The trueness parameter was also assessed by estimating method-level differences from zero. The significance criterion was set at $\alpha = 0.05$. The statistical package Stata was used for data handling and analysis.

3. Results

3.1. *24–27 inside*

The analysis revealed statistically significant differences in precision and trueness between the direct and indirect method: the direct approach (mean [SD] deviation from the reference value: 22.3 [40.0] μm) was more accurate than the indirect one (−40.3 [79.7] μm) (Fig. 3, Table 1). As to trueness, the average deviations differed significantly between methods ($p = 0.012$), and those of the direct methods also differed from zero ($p = 0.002$), in contrast to the indirect method ($p = 0.092$), which is explained by greater measurement uncertainty. Precision was significantly poorer for the indirect method both by interquartile range regression ($p = 0.033$) and equality-of-variances testing ($p = 0.007$). There was no significant

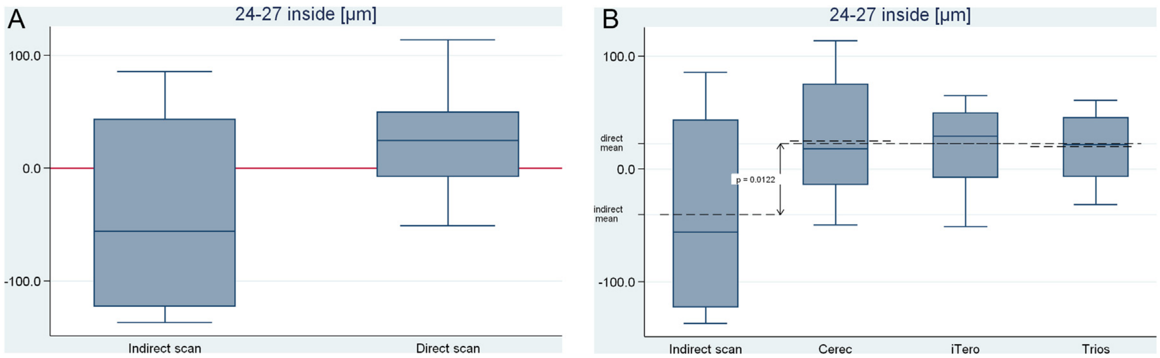

Fig. 3 – Box-plots of inside (24–27) distance measurements. Values are in μm and centred at the reference distance.

Table 1 – Means, standard deviations (SD) and interquartile ranges (IQR) of departure from the reference value in μm for each measured distance.

	24–27 inside	24–27 outside	21–27 left side
Direct mean	22.31	115.82	−163.45
Indirect mean	−40.26	5.18	−325.81
Direct SD	40.00	50.67	145.47
Indirect SD	79.67	111.32	134.13
Direct IQR	57.50	51.60	114.80
Indirect IQR	165.90	166.20	288.90

difference between the different direct systems either in precision or in trueness.

3.2. *24–27 outside*

The indirect system was superior in terms of trueness (mean [SD] deviation from reference, direct method, 115.8 [50.7] μm; indirect method, 5.2 [111.3] μm; $p = 0.001$ for between-methods trueness difference) (Fig. 4, Table 1). The mean deviation from zero was non-significant for the indirect ($p = 0.877$) and strongly significant ($p < 0.001$) for the direct method. There was no significant difference detected in precision between the two approaches using interquartile range regression ($p = 0.111$), although the variances were observed to be substantially different ($p < 0.001$). A significant trueness advantage of the Cerec Omnicam system was observed in comparison to the average of the direct systems ($p < 0.001$). There was no significant difference in precision between the direct methods.

3.3. *21–27 left side*

The analysis revealed a statistically significant difference in trueness between the direct (mean [SD] deviation from reference: −163.5 [145.5] μm) and indirect method (−325.8 [134.1] μm; $p < 0.001$ for between-groups difference). Both approaches significantly underestimated the distance ($p < 0.001$), but there was no significant difference in precision between them (Fig. 5, Table 1). A significantly superior trueness of the iTero system was observed in comparison to the average of all direct systems ($p = 0.008$), which did not differ significantly in terms of precision.

4. Discussion

Studies show that digital intraoral scanners have the advantage of producing a more accurate virtual cast than PVS impression [34,35] or indirect digitalization [13] when digitizing a single prepared tooth. The reason could be that scanners were first designed to make digital impressions of only one prepared tooth [12]. Other studies [22] showed this distortion to be acceptable for making restorations in daily practice. In the case of full arch digitalization, some studies showed no significant difference [36] or the indirect digitalization was more accurate [37]. Most in vitro studies reveal that intraoral scanners only achieve higher accuracy in single unit scans; at the range of full-arch scans, they fail to produce superior accuracy compared to conventional techniques [38,39]. One study showed that scanning can only be clinically acceptable within the range of less than half an arch [40].

To assess the accuracy of methods, some studies compare the fit of the final restoration, other studies compare the surface tessellation language (STL) datasets [13]. In this study the STL files were compared and the deviation from the reference model was investigated based on the ISO Norm 5725-1 standard; trueness and precision were calculated.

The results revealed that for the medium distance (a single bridge restoration), the indirect CAD/CAM scanning method had superior trueness but inferior precision in comparison to direct scanning. The average deviation of indirect measurements from the true value was very close to zero; however, they varied greatly in comparison to remarkably higher levels of precision achieved by all three intraoral scanners. At the range of half-arch digitalization (long distance), the difference between direct and indirect methods became smaller. Trueness was better with the direct systems, and there was no significant difference in precision. Looking at the tendency observed in the study, the imaging procedure of the scanners probably entails errors that accumulate over longer distances scanned. This result is consistent with other studies [40]. The trueness improvement of the iTero long distance scan might be explained by the stitching mechanism of the system. The more reference points the system found, the better it performed in terms of stitching. It must be mentioned that this study was not carried out under clinical conditions. Few studies are made in vivo [41–43]. Looking at the in vivo

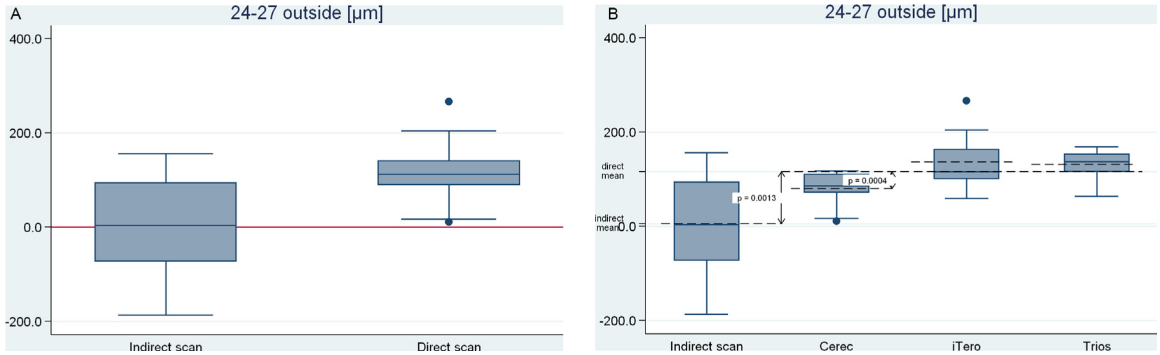

Fig. 4 – Box-plots of outside (24–27) distance measurements. Values are in μm and centred at the reference distance.

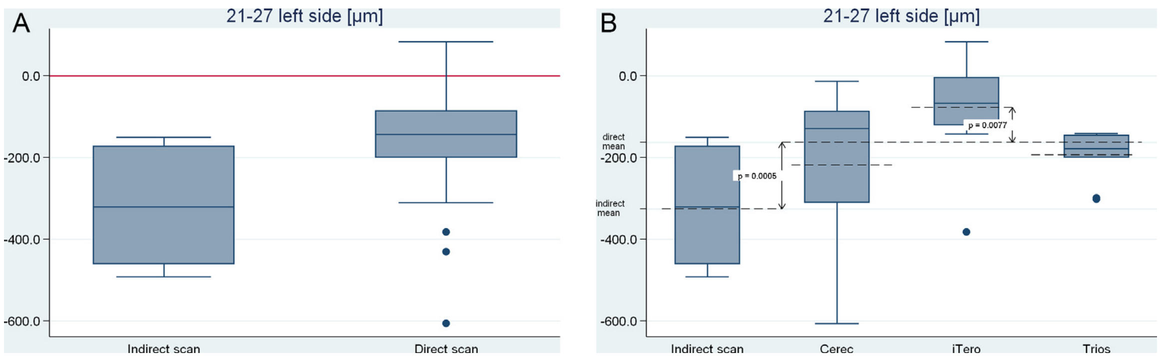

Fig. 5 – Box-plots of half-arch (21–27) distance measurements. Values are in μm and centred at the reference distance.

accuracy of the indirect CAD/CAM method, the range can be influenced by the impression material, tray material, casting material, casting and sectioning procedure, scanning procedure, etc. As to the in vivo accuracy of intraoral scanners, results can be influenced by the scanning protocol [44], saliva, patient movement, [15] soft tissue, number of additional scans, and automatic correction of missing data. Studies show that digital impression needs less time and its use is more comfortable for both patients and operators [7,30]. However, digital intraoral impression systems still have one essential problem: the scanners are optical systems which can only capture the visible regions. Subgingival finishing lines, saliva or blood, patient movement, and the lack of space for operating with the scanner mainly in the molar region can negatively affect the accuracy of direct digitalization in vivo [45]. The few available in vivo studies show that digital impression systems are time-efficient and capable alternatives of conventional impression up to the range of a quadrant; however, at complete-arch ranges, scanners are prone to greater local deviations due to various technical factors – such as normal vector orientation, variations of surface resolution, challenges of surface data post processing – aggravated by the difficulties posed by in vivo spatial conditions [42,43].

The accuracy of virtual casts obtained by direct and indirect methods should be measured by digitizing patients' arches. Digital workflow has the potential to improve the standard of treatment and allow new methods, materials of production, and new treatment concepts [15]. Enhanced direct feedback on screen during the digital impression procedure is of great utility to the operator and can help dentists to improve their skills. Direct data capturing technology offers results comparable to those achieved using well-established conventional digital data capturing methods [13]. Further in vivo studies measuring the accuracy of direct and indirect scanning are necessary.

5. Conclusions

Within the limitations of this in vitro study, it was concluded that the accuracy of both methods was influenced by the length of the arch included in the impression. The shorter the distance, the more accurate results were achieved. Intraoral scanning of the shortest distance of the arch (24–27 inside) delivered more accurate results than the indirect CAD/CAM method. For the medium distance (24–27 outside), both the direct and the indirect method produced a less accurate result than for 24–27 inside. However, the direct method seemed to be more consistent at this distance than the indirect one. In the case of the half arch (21–27 left side), both methods were less accurate than at inside and outside, and the direct method's precision advantage decreased. Virtual models obtained by digital impressions can be more accurate than virtual models based on the conventional method of laboratory scanning. Technically it would be possible to replace conventional impressions with digital intraoral scans. Further investigations are needed to clarify the accuracy in vivo.

Please cite this article in press as: Vecsei B, et al. Comparison of the accuracy of direct and indirect three-dimensional digitizing processes for CAD/CAM systems – An in vitro study. J Prosthodont Res (2016), http://dx.doi.org/10.1016/j.jpor.2016.07.001

5.1. *Clinical aspects*

In light of the results, it can be established that the longer the arch to scan, the less accurate the methods. The difference between the two methods decreases, but even with a half arch, the direct approach is still more accurate. Digital impressions provide more accurate virtual casts compared to virtual models made by indirect CAD/CAM methods.

Conflict of interest

The authors declare that there are no conflicts of interest.

Acknowledgments

Special thanks to VARINEX Informatics Inc. for their helpful contribution.

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