Lea Sophia Prott, Ralf Joachim Kohal, Kirstin Vach, Gary David Hack, Sebastian Berthold Maximilian Patzelt

Accuracy of computerized optical impression making: the influence of different scan paths

Introduction: The aim of this in vitro study was to investigate the influence of different scan paths on the accuracy of digital full arch impressions obtained by 3 scanning systems.

Materials and methods: A maxillary model with 14 prepared teeth was digitized with a reference scanner (ATOS III Triple Scan) and 3 test scanners (CS 3500, CEREC Omnicam and True Definition) using 7 different scan paths. In test path 1 and 2, the manufacturers' suggested scan paths were investigated. In test path 3, 4, and 5 shorter scan paths were utilized. For comparison, a randomly selected scan path was performed in test path 6. Test path 7 was a repetition of scan path 1 to investigate whether there was a learning effect. The scans were digitally superimposed (Geomagic Control), values for trueness and precision were evaluated and statistical analyses performed.

Results: Path 4 (trueness: 32.7 ± 10.3 µm, precision: 23.8 ± 9.5 µm) and path 5 (trueness: 35.1 ± 10.7 µm, precision: 24.2 ± 10 µm) revealed the highest accuracy. For trueness measurements of Omnicam, no statistically significant differences were found between individual scan paths. Overall, path 7 showed a higher accuracy than path 1, however, the differences were not statistically significant.

Conclusion: Ideally, the selected scan path should be as short as possible, and long-distance scans should be avoided. The accuracy of Omnicam appeared not to be dependent on a specific scan path. For all three scanners, the accuracy was clinically acceptable, however, the scan of a prepared full arch with a point-and-click system (CS 3500) cannot be recommended.

Keywords: computerized optical impression making; digital impression; optical impression; scan path; scan pattern

Department of Prosthodontics, Medical Faculty and University Hospital Düsseldorf, Heinrich-Heine-University Düsseldorf, Moorenstraße 5, 40225 Düsseldorf, Germany: Lea Sophia Prott, DDS, Dr med dent, Assistant professor (correspondig author)
Medical Center – University of Freiburg, Center for Dental Medicine, Department of Prosthetic Dentistry, Faculty of Medicine, University of Freiburg, Germany: Ralf Joachim Kohal, DDS, Prof. Dr. med. dent. habil. (PhD equiv.), Associate Professor, Sebastian Berthold Maximilian Patzelt, DMD, MSc, PD Dr. med. dent. habil. (PhD equiv.), Adjunct Professor for Computerized Dentistry, Private Dental Clinic, Zimmern o. R., Germany: Sebastian Berthold Maximilian Patzelt, DMD, MSc, PD Dr. med. dent. habil. (PhD equiv.), Owner
Center for Medical Biometry and Medical Informatics Institute for Medical Biometry and Statistics, Medical Center – University of Freiburg, Freiburg, Germany: Kirstin Vach, Statistician
Department of Advanced Oral Sciences and Therapeutics, University of Maryland School of Dentistry, Baltimore, MD, USA: Gary David Hack, DDS, Associate Professor
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Scanner / Path	CS 3500		Omnicam		True Definition	
	Mean	SD	Mean	SD	Mean	SD
1	71.6	7.7	28.2	8.5	45.2	13.0
2	52.6	8.9	31.0	8.7	45.8	8.1
3	45.0	5.7	23.7	6,0	50.0	11.1
4	44.1	4.6	22.3	2.1	31.6	7.3
5	43.2	9.8	27.2	7.4	34.8	8.6
6	52.0	11.8	28.0	9.8	43.8	11.0
7	64.0	9.2	26.1	4.3	39.7	6.6

Table 1 Mean deviations and standard deviations (SD) for trueness of all test groups in µm.

1. Introduction

To produce high-quality dental restorations, it is necessary to make an impression of the prepared teeth which ideally should be as accurate and detailed as possible. For intraoral scanning, the accuracy is specified in terms of trueness and precision (ISO 5725-1) [14]. Trueness describes the extent of deviation between test and reference measurements, whereas precision is defined as the consistency among the test measurements obtained by a comparison of the repeated intraoral scans [35]. Only trueness and precision together may describe the accuracy of a digital impression [7]. However, the quality of a restoration corresponds to the sum of errors of each individual step in a digital workflow [25]. Errors that occur during the impression making process can usually not be compensated for in the subsequent steps [43]. The main advantages of computerized optical impression making are the increased patient comfort, the savings of working time and the elimination of errors caused by the conventional impression material or during the production of the stone model [33, 43, 51]. In previous studies, full arch digital impressions revealed an equal or higher accuracy than that achieved with conventional impression materials [6, 32, 46]. Nevertheless, in 2021 only half of the American dentists used an intraoral scanner in their practice [38]. 66 % of the nonusers mentioned the high level of financial investment as the main reason. Against this, digital devices, such as intraoral scanners and milling machines, are already well established in dental technology [1]. Even in other fields of dentistry, like orthodontics or maxillofacial surgery, digital technologies are already an integral part of treatment for the calculation of indices, treatment follow-ups and the simulation of treatment plans in advance [10, 22].

The accuracy of digital impressions is affected by the extension of the area to be scanned [9, 46, 53]. During optical data acquisition, 3D single images are stitched together by overlaying and merging the edge areas of the point clouds of 2 single images [25]. Thereby, any inaccuracies sum up to larger errors in the resulting 3-dimensional dataset. Previous in vitro studies examining the acquisition of full arches demonstrated that most scanning systems are able of capturing a full arch with sufficient accuracy, however, there is a need for improvement to achieve the level of conventional impression making [7–9, 15]. Moreover, there is a lack of studies investigating the accuracy of full arch impressions in patients [6, 17, 20, 23, 42].

To reduce measurement errors in larger scan areas, it seems to be necessary to find a process where the individual images are not lined-up along the dental arch, but rather are stitched together in such a way that errors due to superimposition are kept to a minimum. This may be achieved, for example, by additional lateral images or by crossing the occlusal surface [54]. The influence of scan paths on the accuracy of full arch impressions has been demonstrated in previous studies [5, 8, 24, 28, 30, 45]. However, these studies used dentate models with no preparation or with a maximum of 2 prepared teeth. To represent a more complex situation, the present study contains a model with 14 prepared teeth. Moreover, there is still no consensus in literature which scan path is the most appropriate one, especially for using different scanning systems. Since the evidence whether the manufacturer's scan path is really superior to others is lacking, the present study compared different shorter scan paths to the more complex scan paths of the manufacturers.

Previous studies reported that the learning curve was highest for low-experienced operators [19, 37, 49], however, the learning curve of an experienced operator may still be steep when using another intraoral scanner [52]. Moreover, it is reported that the accuracy of newer scanning systems is less likely be influenced by the user's experience [22]. To analyze this learning effect, the second objective of the study was to investigate if there is an effect of increasing experience due to the large number of scans performed. The tested null hypotheses were that (I) the 7 different scan paths and (II) the user's experience do not affect the accuracy of digital impressions obtained by 3 different scanning systems.

2. Materials and methods

A maxillary dental model (Prosthetic Restauration Jaw Model (PRO2001-UL-SP-FEM-32), Nissin Dental Products INC., Kyoto, Japan) with screwable typodont teeth (Simple Root Tooth Model (A5A-200), Nissin Dental Products INC.) was used in the present study. The model was duplicated and an acrylic replica (Self-curing denture, Lang Dental, Wheeling, IL, USA) was fabricated. The typodont teeth 17–27 were embedded into the acrylic model and were prepared with a shoulder to accept all-ceramic crowns. In order to create a reference data set, the model was firstly digitized with a highly accurate industrial scanner (ATOS III Triple Scan, GOM GmbH, Braunschweig, Germany). Subsequently, the reference model was scanned with 3 intraoral scanning systems: CS 3500 (Carestream Health, Rochester, NY, USA), CEREC AC Omnicam (Dentsply Sirona GmbH, Bensheim, Germany), and True Definition (3M ESPE, Seefeld, Germany). The following software versions were used: CS 3500 (Dental Imaging Software, Version 1.2.6.50), Omnicam (Version SW 4.4.0.122433), True Definition (Version 5.0.2-production-eu).

Overall, 7 different scan paths were tested and each scan path was performed 5 times [31, 32, 34]. For the scan of a full arch, Dentsply Sirona [4] and 3M ESPE recommended a specific scan path. Carestream Health did not provide any information about a full arch scan for the CS 3500. Therefore, the manufacturer's scan path of the Omnicam was used. For True Definition, the recommended manufacturer's scan path as well as video instructions for powdering and camera positioning were available on the computer interface. In test path 1, the scan path recommended by the manufacturer was investigated. In path 2, the manufacturer's scan path of the other tested scanner was used. In path 3, 4, and 5 shorter scan paths were investigated, which were previously tested in a study by Ender and Mehl [8]. For comparison, a randomly selected scan path was chosen in path 6. In path 7, the manufacturer's scan path used in path 1 was repeated in order to investigate if there is a learning effect due to the large number of scans. All scan strategies are displayed in a representative illustration (Figure 1). In this present study, the completeness of the datasets was mandatory. After the implementation of the respective scan path scanning was continued until relevant missing areas above the preparation margins were sufficiently captured. The overall scanning time was recorded.

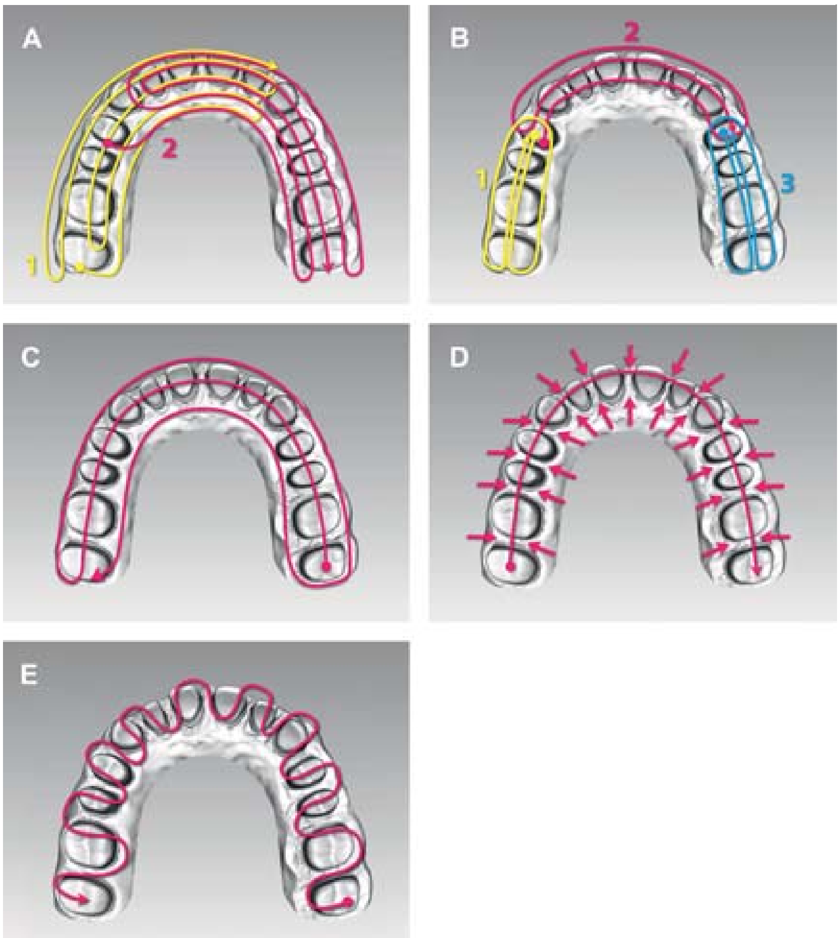

Figure 1: L.S. Prott

Figure 1
A) Manufacturer's recommended scan path of the Omnicam:
First half of arch: Starting occlusally at tooth 17 (1, yellow), the camera was tilted at a 45° angle to the palatal and guided anteriorly to tooth 22, where it was rotated another 45° and then returned to tooth 17, now at a 90° angle. From there, it was directed back to the occlusal surface of tooth 17 and then moved anteriorly back to tooth 22, where the camera was rotated 45° to the buccal and then guided posteriorly back to tooth 17. Buccally on tooth 17, the camera was rotated another 45° and then moved back anteriorly at a 90° angle. Second half of arch: Starting occlusally at tooth 14 (2, red), from where the camera was rotated at a 90° angle to the palatal and guided along the dental arch to tooth 27. There, the camera was tilted back to a 45° angle and then guided to tooth 12, where it was panned over and then guided buccally at a 45° angle to tooth 27. It was tilted again at a 90° angle and moved back to 12. The camera was rotated occlusally and finally returned to 27.

B) Manufacturer's scan path of the True Definition: Starting from tooth 14 occlusally to the distal surface of 17, the camera was moved back palatally to 14. Then panned buccally and returned to tooth 17. Subsequently it was directed occlusally back to 14 (1, yellow). Secondly, the camera was guided palatally from 14 to 24 in a vertical position. It was then panned over 24 and directed labially back to 14. Starting from 14, the incisal surface was scanned back to 24 (2, red). Started occlusally at tooth 24 and the camera was guided from there distally to 27. Then palatally back to 24 and then buccally to 27. The scan path ended occlusally (3, blue).

C) Scan path 3 (Straight): Starting occlusally at tooth 27, the camera was guided along the dental arch to tooth 17. Then the buccal and finally the oral surfaces were scanned.

D) Scan path 4 (Panned): The scan started occlusally at tooth 17 and the camera was guided along the dental arch to tooth 27. Subsequently it was panned at an angle of approximately 30° from oral, then from buccal.

E) Scan path 5 (Cross): The scan started occlusally at 27 and the camera was moved along the dental arch in slow zigzag movements from oral to buccal to tooth 17 (tooth numbers are noted according to the FDI World Dental Federation notation system).

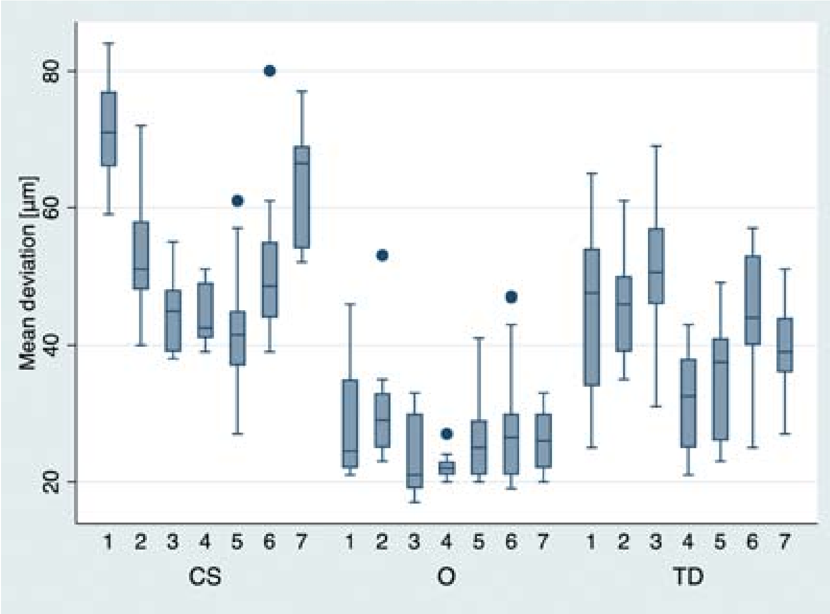

Figure 2: K. Vach

Figure 2 Mean deviations of all test groups for the trueness measurements (CS = CS 3500, O = Omnicam, TD = True Definition).

For CS 3500, datasets could be exported directly to open STL files. Against this, the files of Omnicam had to be exported as encrypted dxd files, since the CEREC workflow was still a closed system at the time of this study. The conversion into open STL files was carried out with the Sirona Connect software (Version SW 4.4.1.132174) and InLab (Version SW 15.1.0.135929). For True Definition, the datasets had to be sent to a proprietary cloud platform (3M Connection Center) for conversion and were downloaded as open STL files. Before scanning, the model was pretreated with dusting powder (3M High Resolution Scanning Spray, 3M ESPE, Saint Paul, MN, USA). The CS 3500 and the Omnicam scanner did not need any powdering.

All scans were performed by a dental student (L.P.) on several consecutive days. On these days, the humidity was at 21 ± 12 % and the room temperature at 24 ± 3 °C. The student trained herself to perform the scans for a week beforehand, performing 30 practice scans with each scanner.

For evaluation, the STL files of the reference scanner and the test scanners were loaded into a 3D analysis software (Geomagic Control 2014, 3DSystems, Rock Hill, SC,USA). Using Geomagic's initial alignment and the best-fit algorithm, the datasets were superimposed by determining the minimal distance between 2 closest surface points of the test and reference file. Subsequently, 3D comparisons were performed and mean values as well as positive and negative mean deviations were calculated. The deviations between the datasets of the test scanners and the reference scan (trueness) and the deviations of the data sets within a test group (precision) were determined. For trueness, a total number of 35 comparisons were performed (5 comparisons per test group, 7 test groups). For precision the number of comparisons was 70 (10 comparisons per test group, 7 test groups). Color-coded images were exported for visual evaluations.

For descriptive statistical analysis means, medians and standard deviations (SD) were computed. Linear mixed models were fitted with random intercepts for each scan strategy to evaluate device effects on response variables. The method of Scheffe was applied to address the multiple testing problem due to several pairwise comparisons. The calculations were performed with a statistical software (STATA 14.2, StataCorp LP, College Station, TX, USA). The level of statistical significance was set to $p \leq 0.05$.

3. Results

The results for trueness of all test groups are shown in Table 1 and are graphically displayed in Figure 2. The comparisons between the individual scan paths are given in Table 2. For the CS 3500, the datasets in path 4 (44.1 ± 4.6 µm) and in path 5 (43.2 ± 9.8 µm) deviated the least from the reference scan. There were statistically significant differences between path 1 and 2 (19 ± 3.6 µm, p = 0.000), 1 and 3 (26.6 ± 3,6 µm, p = 0.000), 1 and 4 (27.5 ± 3.6 µm, p = 0.000), 1 and 5 (28.4 ± 3.6 µm, p = 0.000), 1 and 6 (19.6 ± 3.6 µm, p = 0.000), 3 and 7 (19 ± 3.6 µm, p = 0.000), 4 and 7 (19.9 ± 3.6 µm, p = 0.000) and 5 and 7 (20.8 ± 3.6 µm, p = 0.000). The visual analysis showed high deviations above 100 µm especially in the molar regions (Figure 3). The trueness measurements of the Omnicam were best in path 3 (23.7 ± 6 µm) and 4 (22.3 ± 2.1 µm). There were no statistically significant differences between the individual scan paths. In the higher deviating test paths of the manufacturers' scan paths, datasets with positive deviations occlusally and buccally with simultaneously occurring negative deviations on the oral surfaces were frequently found (Figure 4). The True Definition datasets deviated least from the reference scan in path 4 (31.6 ± 7.3 µm) and path 5 (34.8 ± 8.6 µm). Statistically significant differences were found between path 2 and 4 (14.2 ± 3.9 µm, p = 0.038), 3 and 4 (18.4 ± 3.9 µm, p = 0.001) and 3 and 5 (15.2 ± 3.9 µm, p = 0.018). All scan paths of the True Definition showed a wavy deviation pattern from occlusal. Orally, negative deviations occurred, while buccally, especially in the posterior regions, there were high positive deviations more frequently (Figure 5).

The precision results are given in Table 3. Figure 6 displays graphs of the mean deviations, and the comparisons between the individual scan paths are given in Table 4. The precision of the CS 3500 was lowest in path 1 (25.5 ± 5.7 µm). Statistically significant differences were found between the paths 1 and 2 (16.3 ± 3 µm, p = 0.000), 1 and 6 (14.7 ±

Scanner / Path	CS 3500			Omnicam			True Definition		
	Mean	SEM	p-value	Mean	SEM	p-value	Mean	SEM	p-value
1 vs. 2	19.0	3.6	**0.000**	2.8	3.0	0.990	0.6	3.9	1.000
1 vs. 3	26.6	3.6	**0.000**	4.5	3.0	0.899	4.8	3.9	0.958
1 vs. 4	27.5	3.6	**0.000**	5.9	3.0	0.704	13.6	3.9	0.058
1 vs. 5	28.4	3.6	**0.000**	1.0	3.0	1.000	10.4	3.9	0.308
1 vs. 6	19.6	3,6	**0.000**	0.2	3.0	1.000	1.4	3.9	1.000
1 vs. 7	7.6	3.6	0.609	2.1	3.0	0.998	5.5	3.9	0.920
2 vs. 3	7.6	3.6	0.609	7.3	3.0	0.444	4.2	3.9	0.979
2 vs. 4	8.5	3.6	0.466	8.7	3.0	0.220	14.2	3.9	**0.038**
2 vs. 5	9.4	3.6	0.332	3.8	3.0	0.954	11.0	3.9	0.239
2 vs. 6	0.6	3.6	1.000	3.0	3.0	0.986	2.0	3.9	1.000
2 vs. 7	11.4	3.6	0.119	4.9	3.0	0.855	6.1	3.9	0.873
3 vs. 4	0.9	3.6	1.000	1.4	3.0	1.000	18.4	3.9	**0.001**
3 vs. 5	1.8	3.6	1.000	3.5	3.0	0.970	15.2	3.9	**0.018**
3 vs. 6	7.0	3.6	0.701	4.3	3.0	0.918	6.2	3.9	0.864
3 vs. 7	19.0	3.6	**0.000**	2.4	3.0	0.996	10.3	3.9	0.321
4 vs. 5	0.9	3.6	1.000	4.9	3.0	0.855	3.2	3.9	0.995
4 vs. 6	7.9	3.6	0.562	5.7	3.0	0.738	12.2	3.9	0.132
4 vs. 7	19.9	3.6	**0.000**	3.8	3.0	0.954	8.1	3.9	0.632
5 vs. 6	8.8	3.6	0.419	0.8	3.0	1.000	9.0	3.9	0.500
5 vs. 7	20.8	3.6	**0.000**	1.1	3.0	1.000	4.9	3.9	0.954
6 vs. 7	12.0	3.6	0.082	1.9	3.0	0.999	4.1	3.9	0.981

Table 2 Mean deviations with standard errors of the mean (SEM) and p-values for the trueness comparisons of the individual scan paths in µm. Significant differences ($p \leq 0.05$) are highlighted.

3 µm, p = 0.001), and 2 and 5 (11.7 ± 3 µm, p = 0.021). For the Omnicam, the datasets in path 7 (15.1 ± 4.3 µm) deviated least. There were statistically significant differences between paths 1 and 2 (8.4 ± 2.1 µm, p = 0.014), 1 and 4 (8.9 ± 2.1 µm, p = 0.006), 1 and 7 (9.2 ± 2.1 µm, p = 0.004), and 6 and 7 (7.6 ± 2.1 µm, p = 0.042). For the True Definition, the lowest deviation was found in path 2 (19.9 ± 5.6 µm). There were statistically significant differences between paths 1 and 6 (13.6 ± 3.3 µm, p = 0.012), 2 and 3 (18.8 ± 3.3 µm, p = 0.000), 2 and 6 (24.9 ± 3.3 µm, p = 0.000), 2 and 7 (15.7 ± 3.3 µm, p = 0.001), 3 and 4 (13.9 ± 3.3 µm, p = 0.009), 3 and 5 (15.1 ± 3.3 µm, p = 0.003), 4 and 6 (20 ± 3.3 µm, p = 0.000), 5 and 6 (21.2 ± 3.3 µm, p = 0.000),

Scanner / Path	CS 3500		Omnicam		True Definition	
	Mean	SD	Mean	SD	Mean	SD
1	25.5	5.7	24.3	10.9	31.2	10.6
2	41.8	13.3	15.9	2.6	19.9	5.6
3	33.2	8.3	17.4	5.8	38.7	12.7
4	31.3	8.5	15.4	3.8	24.8	7.6
5	30.2	9.0	18.9	6.9	23.6	10.8
6	40.2	12.1	22.6	9.3	44.8	15.5
7	35.0	9.7	15.1	4.3	35.6	13.3

Table 3 Mean deviations and standard deviations (± SD) for precision of all test groups in µm.

and 5 and 7 (12 ± 3.3 µm, p = 0.047). Regarding the precision of all scanners, the highest deviations were found primarily in the molar regions.

The scanning times result from the execution of the scan path, the rescanning and the processing of the dataset. The average scanning time (+ SD) for the CS 3500 was 34 ± 3.4 minutes and 17 ± 5.7 minutes for the Omnicam. For the True Definition, a maximum scanning time of 7 minutes was default by the scanner. After the practice scans, it was reliably possible to capture the whole model in these 7 minutes, however, for all True Definition scans the maximum scan time of 7 ± 0 minutes was applied.

Regarding a learning effect, path 7 showed a higher accuracy than path 1, however, these differences were only statistically significant for the precision of Omnicam. The learning curve can therefore be regarded as minor.

4. Discussion

The aim of this in vitro study was to examine the effect of seven different scan paths on the accuracy of 3 commercially available intraoral scanners. For a dataset to be considered accurate, both parameters, trueness and precision, must be within an acceptable range. Deviations across the full arch of less than 100 µm are accepted since deviations of 100 µm and above may cause an non-acceptable fit of the produced restorations [7]. Based on the present results, the null hypothesis (I) was rejected as the applied scan paths affected the accuracy of digital impressions. However, for trueness measurements of the Omnicam, no statistically significant differences were found between the individual scan paths. Also Passos et al. [30] reported previously, that there was no dominant strategy for trueness and precision measurements with the Omnicam.

Overall, path 4 (Panned) and 5 (Cross) achieved the highest accuracy. In path 4, the camera was first moved occlusally along the dental arch and then panned at a 30° angle from oral and buccal. In path 5, the dental arch was scanned in slow zigzag movements. In a study by Ender and Mehl [8], the panned scanpath also reached the lowest deviation, while Cross was statistically significant worse. In contrast, Van der Meer et al. [48] found the lowest measurement errors with the zigzag scan path. Ender and Mehl [8] suspected that these deviations could have been due to the different analysis procedures as they superimposed the scans in a 3D evaluation software, while Van der Meer et al. [48] measured the inclinations and distances between 3 cylinders. However, it should be mentioned that in the study by Van der Meer et al. [48] only the Lava C.O.S. used a specific scanning protocol. Furthermore, all scanners used a different principle of acquisition and differed in the use/not-use of powder. Medina-Sotomayor et al. [26] also achieved the best results with a zigzag scan path. Keul and Güth [16] found a scan path, that performed a zigzag scan of both quadrants, with an additional overlapping in the anterior region, most suitable. Likewise, other authors concluded that the accuracy can be increased by additional angled images and crossing over the occlusal surface [11, 21, 27]. This might be an advantage, because more data could be acquired in the hard-to-reach approximal regions during execution of the scan path. Additionally, more information might be obtained by taking additional overlapping angled images, especially in the more inclined and less structured anterior areas [27]. A recent study reported significant differences in measurements made within a quadrant compared to intermolar or inter-canine distances [23], which were traced back to greater errors occurring in the incisor region. Consequently, the selection of an appropriate scan path seems to be particularly important to minimize stitching errors in the anterior region, simultaneously, this leads to a reduction of the high deviations frequently found in the molar regions.

In the present study, all tested scanners achieved greater accuracy utilizing shorter scan paths than with the more complex scan paths suggested by the manufacturers. For trueness of the CS 3500, no statistically significant differences between the shorter paths 3, 4 and 5 and the manufacturers' scan paths 1 and 7 were found. In contrast, regarding trueness of Omnicam, there were no statistically significant differences between the individual scan paths. However, also for Omnicam, the trueness values were identified to be most accurate in path 4 (Panned), while the deviation of the manufacturers' scan paths in path 1 and 2 was highest. A possible explanation might be that the more complex manufac-

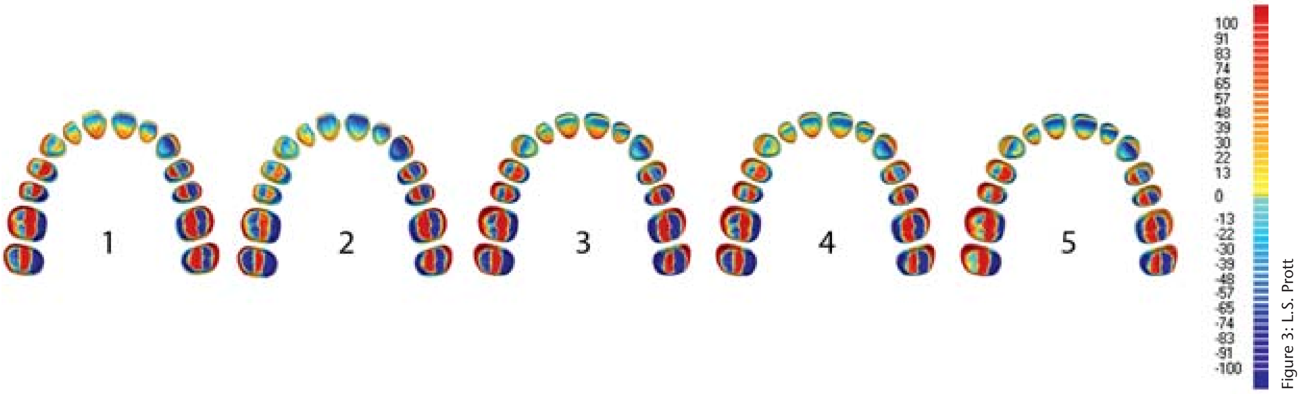

Figure 3 Superimposed datasets of the reference scanner and CS 3500 (dark blue ≤ –100 µm, dark red ≥ +100 µm deviation).

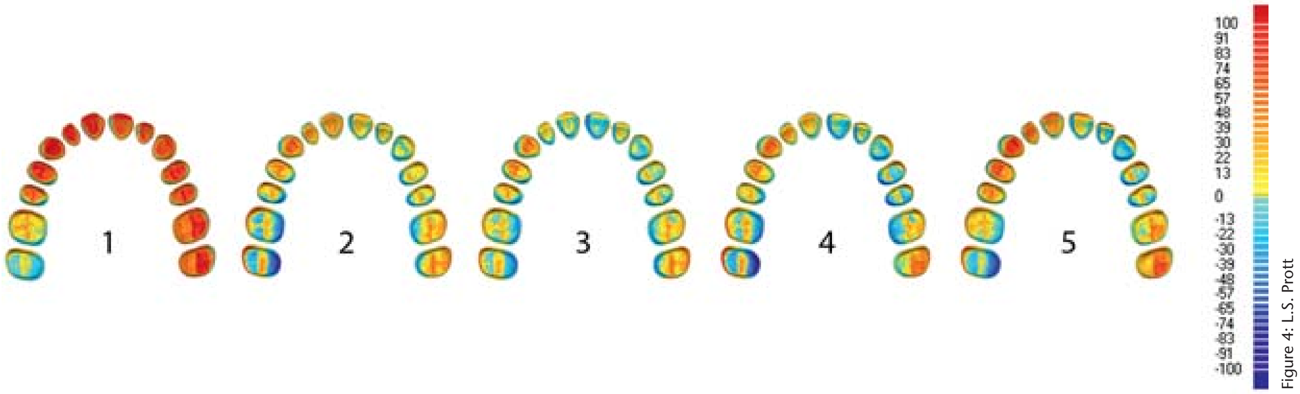

Figure 4 Superimposed datasets of the reference scanner and the Omnicam (dark blue ≤ –100 µm, dark red ≥ +100 µm deviation).

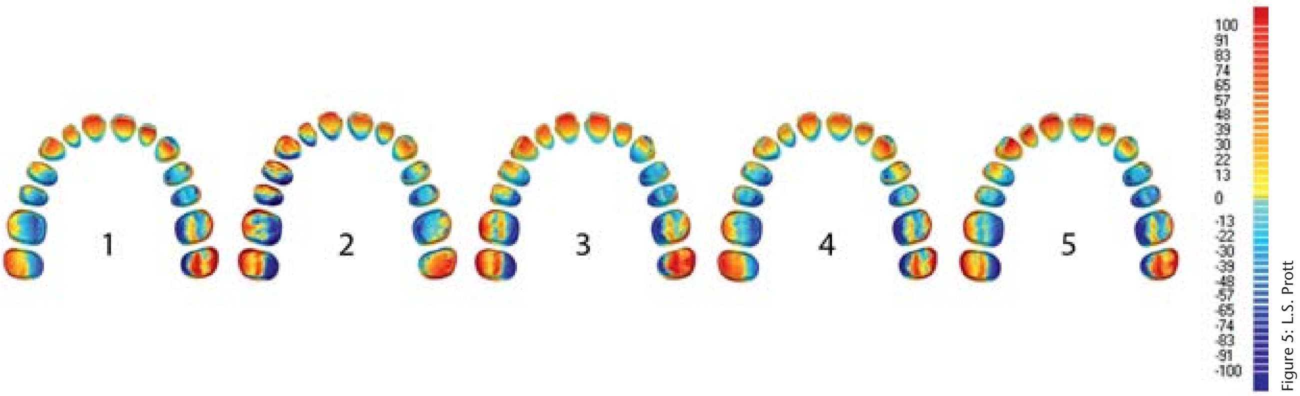

Figure 5 Superimposed datasets of the reference scanner and the True Definition (dark blue ≤ –100 µm, dark red ≥ +100 µm deviation).

turers' scan paths had a higher number of errors due to the large number of individual images that needed to be stitched together. Overall, trueness and precision values of the Omnicam were better than those achieved with the CS 3500. The higher deviations of the CS 3500 may be due to technological differences (point-and-click system) as well as different matching algorithms, filters, lower resolution or interpolation errors [43, 44, 50]. The Omnicam and CS 3500 use the same scanning technology (active triangulation), but they differ in their stitching mechanisms. While the Omnicam is a video-based system, the CS 3500 is a point-and-click system. As mentioned in previous studies, the video-based technology seems to be beneficial for a highly accurate image acquisition [12, 26]. Furthermore, the current literature shows that software versions have a significant influence on the accuracy of intraoral scanners [9, 13], and the ongoing improvements in soft- and hardware will continuously increase the scanning technology [42].

The trueness of the True Definition was highest in path 4 (Panned) and path 5 (Cross) with statistically significant differences to path 3 (Straight). The results obtained with the Omnicam and CS 3500 were not significantly worse in path 3, but issues were observed during the stitching process of the CS 3500 when

Scanner / Path	CS 3500			Omnicam			True Definition		
	Mean	**SEM**	**p-value**	**Mean**	**SEM**	**p-value**	**Mean**	**SEM**	**p-value**
1 vs. 2	16.3	3.0	**0.000**	8.4	2.1	**0.014**	11.4	3.3	0.074
1 vs. 3	7.7	3.0	0.370	6.9	2.1	0.091	7.5	3.3	0.549
1 vs. 4	5.8	3.0	0.728	8.9	2.1	**0.006**	6.4	3.3	0.723
1 vs. 5	4.7	3.0	0,883	5.4	2.1	0.364	7.6	3.3	0.523
1 vs. 6	14.7	3.0	**0.001**	1.7	2.1	0.996	13.6	3.3	**0.012**
1 vs. 7	9.5	3.0	0.129	9.2	2.1	**0.004**	4.4	3.3	0.946
2 vs. 3	8.6	3.0	0.231	1.5	2.1	0.998	18.8	3.3	**0.000**
2 vs. 4	10.6	3.0	0.058	0.6	2.1	1.000	5.0	3.3	0.901
2 vs. 5	11.7	3.0	**0.021**	3.0	2.1	0.914	3.8	3.3	0.974
2 vs. 6	1.6	3,0	1.000	6.7	2.1	0.113	24.9	3.3	**0.000**
2 vs. 7	6.8	3.0	0.535	0.9	2.1	1.000	15.7	3.3	**0.001**
3 vs. 4	2.0	3.0	0.999	2.0	2.1	0.989	13.9	3.3	**0.009**
3 vs. 5	3.1	3.0	0.985	1.6	2.1	0.997	15.1	3.3	**0.003**
3 vs. 6	7.0	3.0	0.498	5.3	2.1	0.389	6.1	3.3	0.767
3 vs. 7	1.8	3.0	0.999	2.3	2.1	0.976	3.1	3.3	0.990
4 vs. 5	1.1	3.0	1.000	3.6	2.1	0.823	1.2	3.3	1.000
4 vs. 6	9.0	3.0	0.187	7.3	2.1	0.061	20.0	3.3	**0.000**
4 vs. 7	3.8	3.0	0.957	0.3	2.1	1.000	10.8	3.3	0.112
5 vs. 6	10.1	3.0	0.086	3.7	2.1	0.791	21.2	3.3	**0.000**
5 vs. 7	4.9	3.0	0.860	3.9	2.1	0.758	12.0	3.3	**0.047**
6 vs. 7	5.2	3.0	0.814	7.6	2.1	**0.042**	9.2	3.3	0.272

Table 4 Mean deviations with standard errors (SEM) and p-values for the precision comparisons of the individual scan paths in µm. Significant differences ($p \leq 0.05$) are highlighted.

scanning longer distances along the buccal and labial surfaces (in path 3). Visible stitching errors already occurred during the execution of the scan path. For the CS 3500 and True Definition the scan path 3 appeared to be rather unsuitable. It seems that scanning in sextants (manufacturer scan path True Definition) had no advantage. However, the deviations could also have been caused by the vertical scan in the anterior region. The authors of a recent study recommend to avoid a rotation of the scan wand, attributing the inferior accuracy to an interruption of the image-stitching process due to the change of direction [29].

Overall, regarding precision, deviations were very high in path 6 (Randomly selected scan path). This demonstrates that precision increases when a scan path is used. The Omnicam's precision values were most accurate by utilizing the manufacturers' suggested scan path. This differs from the trueness values, where the manufacturers' scan paths were often statistically significant worse than the shorter scan paths. The overlapping scan in the less structured anterior region may have had a positive effect on the precision measurements.

In the present study, the scanning time was higher than in other studies [36, 47, 51]. Allegedly, this was due to the prepared study model that was utilized. Other in vitro studies have used an unprepared model or a model with a maximum of 2 prepared teeth so that it was sufficient to move the wand along the approximal space only once. For unprepared teeth a high mesh density is not as relevant as for prepared teeth, where a large number of triangles are necessary to represent the preparation margin precisely [39]. After the scan path was carried out, the datasets of the prepared full arch model showed data gaps in almost all approximal spaces. These gaps were subsequently closed by additional angled images. Because the results of the present study were better than those of Treesh et al. [47] (trueness of Omnicam: 48.8 µm and CS 3500: 84.6 µm) and Renne et al. [36] (trueness of Omnicam: 95.4 ± 10.7 µm and CS 3500: 77 ± 6.5 µm), it can be assumed that the rescanning at least did not have a negative effect on the accuracy of the scans. Due to the different study designs, it is not possible to compare the studies directly. However, with a scanning time of 34 ± 3.4 minutes (including processing and rescanning), the CS 3500 appears clinically unsuitable for the acquisition of a prepared full arch.

Some previous studies used the scanning time for evaluating the learning effect of intraoral scanning [40, 49, 52]. Additionally, the learning curve was determined by measuring deviations or image numbers [35, 37]. As expected, the learning curve was highest for low-experienced operators [19, 37, 49]. Resende et al. [37] found that low experienced operators obtained larger scanning times and the highest number of images compared to more experienced operators. Likewise, Radeke et al.[35] reported that the experience, not the graduation, effected the accuracy. In the present study, the learning effect was evaluated by comparing the accuracy of the same manufacturers' scan paths in group 1 and 7. Overall, path 7 delivered a better result than path 1, but the difference was generally not statistically significant. The learning curve was regarded as minor. In accordance with previous evidence, the authors suspected that the learning effect was probably higher during the exercise scans and subsequently increased only minimally. Thereby, the second null hypothesis that the user's experience does not affect the scan accuracy could be partly rejected.

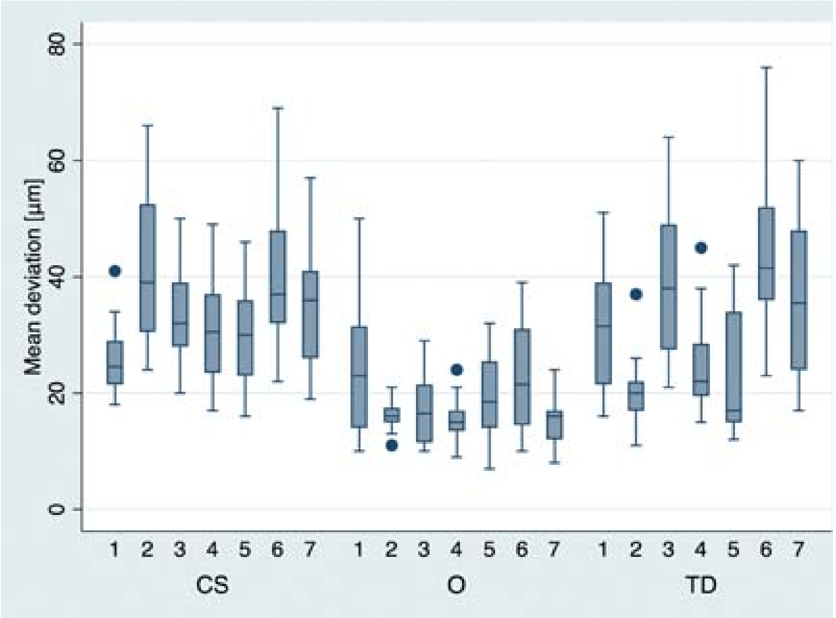

Figure 6: K. Vach

Figure 6 Mean deviations of all test groups for the precision measurements (CS = CS 3500, O = Omnicam, TD = True Definition).

Like in other in vitro studies, clinical conditions like the influence of saliva and blood, limited space, patient movement and different refractive surfaces of tooth substrates and restorations were not considered [3, 41]. Another limitation is the performance of the scans on several consecutive days. Ideally, the study should have been carried out on one day in order to ensure similar conditions. Temperature, humidity and lighting conditions might have affected the present results [2, 18]. Moreover, the used intraoral scanning systems were based on different technology (active triangulation and active wavefront sampling) and differed in their acquisition mode (video sequencing and image acquisition) and the need for powdering. The influence of these system-specific factors is unknown, however, since each scanning system has different characteristics these factors cannot been excluded. Finally, a best-fit algorithm was used for the superimposition of the datasets. For large full-arch datasets the error caused by the point-to-point measurements of the superimposition itself sum up and it remains unknown if and how far the results were influenced by these superimposition errors. However, the superimposition of digitized models is referred to as the standard procedure for 3D surface comparisons [9]. Further research should be undertaken to detect how different scan paths influence the accuracy of full-arch scans in vivo and additional studies with prepared full arch models in vitro would be advisable.

5. Conclusion

Within the limitations of the present study, it can be concluded that there is an effect on the accuracy related to different scan paths when scanning prepared full arches, however, some devices are less sensitive to different scan paths than others. In general, for all tested scanners, the scan path should be as short as possible and long-distance scans should be avoided. In addition, there is a learning curve, however, it can be considered as minor and scanning of prepared full arches with a point-and-click system cannot be recommended.

Conflict of interest

The authors declare that they do not have any conflicts of interest related to the subject matter of this study.

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Photo: L.S. Prott

Corresponding author
DR. LEA SOPHIA PROTT
Department of Prosthodontics
Medical Faculty and
University Hospital Düsseldorf
leasophia.prott@med.uni-duesseldorf.de
Phone +49 211 81-04441
Fax: +49 211 81-16280