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ORIGINAL ARTICLE

Accuracy and eligibility of CBCT to digitize dental plaster casts

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Abstract

Objectives Software-based dental planning requires digital casts and oftentimes cone-beam computed tomography (CBCT) radiography. However, buying a dedicated model digitizing device can be expensive and might not be required. The present study aimed to assess whether digital models derived from CBCT and models digitized using a dedicated optical device are of comparable accuracy.

Material and methods A total of 20 plaster casts were digitized with eight CBCT and five optical model digitizers. Corresponding models were superimposed using six control points and subsequent iterative closest point matching. Median distances were calculated among all registered models. Data were pooled per scanner and model. Boxplots were generated, and the paired *t* test, a Friedman test, and a post-hoc Nemenyi test were employed for statistical comparison. Results were found significant at $p < 0.05$.

Results All CBCT devices allowed the digitization of plaster casts, but failed to reach the accuracy of the dedicated model digitizers ($p < 0.001$). Median distances between CBCT and optically digitized casts were 0.064 + − 0.005 mm. Qualitative differences among the CBCT systems were detected ($\chi^2 = 78.07$, $p < 0.001$), and one CBCT providing a special plaster cast digitization mode was found superior to the competitors ($p < 0.05$).

Conclusion CBCT systems failed to reach the accuracy from optical digitizers, but within the limits of the study, accuracy appeared to be sufficient for digital planning and forensic purposes.

Clinical relevance Most CBCT systems enabled digitization of plaster casts, and accuracy was found sufficient for digital planning and storage purposes.

Keywords CBCT · Plaster casts · Digitalization · Surface matching · Surface distance

Introduction

In dentistry, plaster models play an important role for treatment planning and evaluation of outcomes. Additionally, they act as auxiliary diagnostic tools for clinicians, are handed out to technicians, and are crucial for didactic and research purposes [1].

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Despite their widespread usage, major drawbacks are damage, loss, and storage requirements [2]. In most countries, legal and forensic documentation require yearlong storage, but within an extensive questionnaire conducted in the UK, dentists reported difficulties to comply with the space requirements [3]. Furthermore, physical storage requirements are usually linked to significant costs for dental practitioners [1].

The quest for cost-efficient storage policies has been resolved with the advent of extra-oral and intra-oral dental digitizers which provide satisfactory accuracy validated in several studies [1, 4–6].

Another major benefit of digital models is enabling computer-assisted workflows. For this purpose, 3D planning software usually allows for registration of digital models with x-ray cone-beam computed tomography (CBCT). In implant dentistry, digital planning and guided implant placement were shown to be more accurate compared to unguided procedures [7–11]. In orthodontics, customized appliances such as aligners [12], individualized brackets, and arch wires bent by robots are fabricated based on digital casts. Recent studies indicated that computer-assisted planning and customized fixed appliances can increase treatment effectiveness [13, 14]. Thus, side-effects such as root resorptions which are correlated with treatment duration might be reduced [15].

For research and quality assurance purposes, digital pre- and post-treatment models can be superimposed which allows assessing the actual changes in all three dimensions [16–19].

Despite the technical advantages reported for digital workflows, the potential benefits have to be balanced toward costs. However, for dental practitioners who already operate CBCT devices, buying an additional dedicated optical dental digitizer might not be required. As suggested in previous studies, CT imaging of digital models can be an alternative to digitization with optical devices [1, 2], and contemporary CBCTs provide voxel sizes down to 50 μm.

To simplify adjustment of parameters for CBCT data acquisition, and to simplify segmentation and surface extraction, some vendors started to provide extra cast digitization tools. So far, accuracy of CBCT for model digitization has been poorly evaluated. One study validated reproducibility of software-based automated threshold detection and geometric accuracy of distances between predefined landmarks [20], and another compared geometric accuracy of skull scans [21]. Even though CBCT appears to be a promising all-in-one solution, data is lacking proving eligibility for cast digitization purposes.

The aims of the present study were (i) to evaluate whether digital models derived from CBCT and models digitized using a dedicated optical device are of comparable accuracy, (ii) to compare accuracies with contemporary extra-oral cast digitizers, and (iii) to assess if differences exist between different CBCT systems.

Material and methods

Study design

Twenty models made of plaster (Fa. Wiegelmann Dental GmbH, Bonn, Germany) were selected at random from patients treated at the Department for Orthodontics, University Clinic Dusseldorf, Germany. Half of the models were taken prior to mesialization treatment and presented spaces owing to bilaterally missing maxillary lateral incisors, canines, premolars, first molars, or a space surplus in a full dentate arch. The other half of the models presented the post-treatment situation where the dental arches had been restored by orthodontic space closure. All models were digitized with five different optical devices (3Shape D810, Smart Optics Activity 300, Dentaurum OrthoX, Imetric D105, Zirkonzahn S600) and eight CBCT systems (Acteon Whitefox, Carestream CS 8100 3D, KaVo 3D eXam, Morita Veraviewepocs 3D R100, Morita Accuitomo, Orange Dental Green 3D, Planmeca ProMax 3D Mid). The data acquisition parameters (Tables 1 and 2) were selected based on recommendations of the manufacturers (if available). Segmentation and surface extraction of the CBCT images was performed using the White Fox software (Aceton, Whitefox Imaging Software Version 4.0, Olgiate Olona, Italy). Finally, the data from each digitized model were stored in the stereolithography (STL) file format.

Image processing and registration

The image processing was performed with Meshlab version 1.3.4 beta 2014 (Visual Computing Lab–ISTI–CNR, https://sourceforge.net/projects/meshlab/files/latest/download). First, the models were trimmed digitally such that all parts outside the gingivobuccal folds and the palatal A-line were removed. Then, each model surface obtained from one of the CBCTs was registered with the corresponding digital models obtained from the five optical digitization devices. The datasets representing the plaster models obtained from an optical device were registered with the four corresponding models coming from the remaining optical devices. All registrations were achieved using the "align" feature, six manually placed control points, and a subsequent iterative closest point (ICP) matching (Fig. 1).

Finally, the registered and trimmed models were resampled using the "freeze transformation matrix" option and stored in their new coordinates, which enabled distance analyses (see below).

Distance analysis

Median distances between pairs of registered models were assessed using the "surface distance" tool in Amira 6.1.1 (FEI, Munich, Germany). Since the digital trimming procedure could not eliminate slight differences at the model margins, the median distance, which is insensitive to outliers, was chosen to be the primary outcome.

Since optical devices can be considered to be "gold standard" to digitize plaster models and as manufactures offer resolutions higher than micro-computed tomography (for large field of views, which are needed to digitize the entire plaster cast), this group served as reference within the present investigation. However, since differences among optical systems may exist, five competing optical devices were included in the present study.

To assess accuracy among optical dental digitizers, the "expectation value" x for the median distance between surfaces from different devices was computed for each of the k plaster models using the following formula (d_{ij} the median distance between the registered models

Table 1 Data acquisition parameters for the optical digitization devices

Manufacturer	Name of scanner	Measurement uncertainty (μm)	Remarks
3Shape	D810	Approx. 10	–
Smart optics	Smart Optics Activity 300	Approx. 20	–
Dentaurum	OrthoX	Approx. 20	–
Imetric	D105	Approx. 15	With HD cameras
Zirkonzahn	S600	Approx. 10	–

digitized with device i, $i = 1\ldots5$ and device j, $j = 1\ldots5$, d_i the respective mean value for a model digitized with i):

$$x_k = \frac{1}{5}\sum_{i=1}^{5} d_i,\quad d_i = \frac{1}{4}\sum_{i\neq j} d_{ij}$$

To assess the "expected median distance" (d_{kl}) between plaster model k digitized with a CBCT system l and the optical digitizers $i = 1\ldots5$, the following formula was used:

$$x_{kl} = \frac{1}{5}\sum_{i=1}^{5} d_{il}$$

Statistical analysis

The statistical analysis was conducted using the software program R (R Core Team [22]). Descriptive statistics were computed by calculating means and standard deviations for each group and variable. To assess the reliability and reproducibility of the alignment and distance measurements, a calibration procedure was initiated: Repetition of the $n = 40$ alignment procedures and distance measurements for one randomly selected model revealed that measurements were similar at > 95% level. Welch's t test was used to test for differences between optical digitizers and the CBCT systems (data pooled per model) (hypothesis I: no difference exists in the distances among models digitized optically and using a CBCT). The Friedman test was used to assess qualitative differences among the CBCTs (hypothesis II: no qualitative differences exist in distances among models digitized using a CBCT). A Nemenyi post-hoc test was utilized for pairwise comparison. The results were considered significant at $p < 0.05$.

Results

All CBCT systems enabled digitization of plaster casts (Fig. 2). One manufacturer (Carestream) provided a special holder in conjunction with an extra toolbox for cast digitization within their software program.

Image registration was performed successfully with Meshlab, and subsequent surface distances between the models were computed successfully with Amira software (Fig. 3). Among the dedicated model digitizers, agreement was higher (averaged median distance ± standard deviation, 0.017 ± 0.004 mm) compared to the CBCT systems (averaged median distance to 3D scanners ± standard deviation, 0.064 ± 0.005 mm) (Fig. 4).

When pooling the distances per model and type of scanner, the paired t test yielded a significant mean difference ($p < 0.001$) of 0.046 mm between optical digitizers and CBCT systems. Hence, hypothesis I stating comparable accuracy between digital models obtained

Table 2 Data acquisition parameters for the CBCT systems

Manufacturer	Software, version	kV	mAs	FOV (height × width) (cm)	Total integration time (sec)	Isotropic voxel size (mm)
Acteon, Whitefox	Whitefox, Version 4.1	105	8	8 × 8	9	0.15
Carestream, CS 8100 3D	CS Solutions, Dental Imaging Software, Version 6.14.6.3	80	2	8 × 5	15	0.15
KaVo, OP300 3D	Clinview, Version 10.2.4	90	6.9	8 × 6	6.1	0.2
KaVo 3D eXam	eXam VisionQ, Version 1.9.3.13	120	37.07	8 × 8	20.9	0.2
Morita, Veraviewepocs 3D R100	iDixel, Version 2.2.03	80	3	8 × 8	9.4	0.125
Morita, Accuitomo	iDixel, Version 1.8	90	3	10 × 10	15.8	0.2
Orange Dental, Orange Green 3D	Ex3D2009	90	6	8 × 5	5.9	0.2
Planmeca, ProMax 3D Mid	Romexis Version R.3.8.1	80	12.5	10 × 10	15	0.2

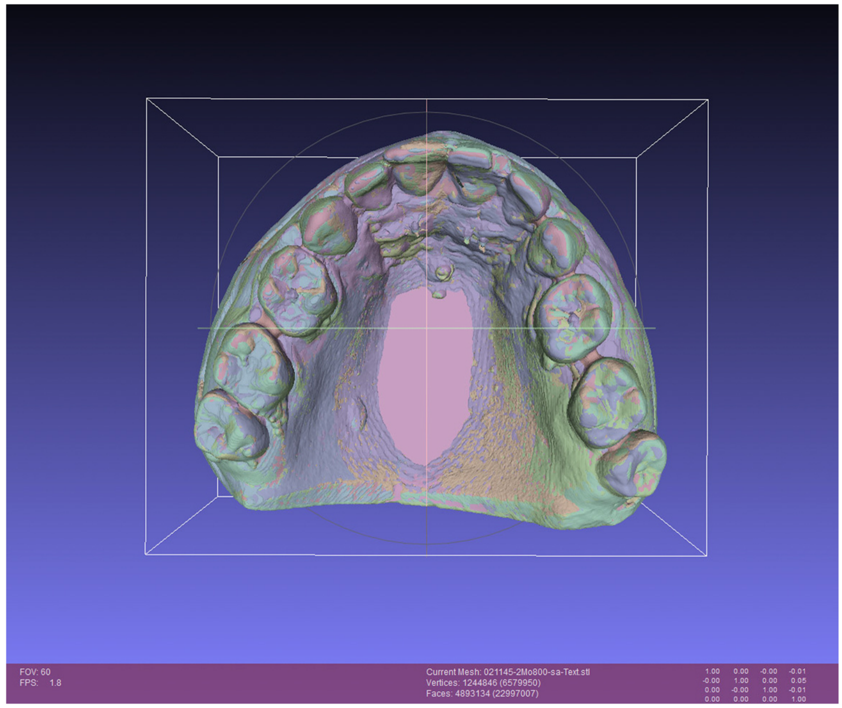

Fig. 1 Registration of corresponding digital models (performed with Meshlab). The models digitized with different devices are represented by different colors

from optical digitizers and CBCT had to be rejected, favoring optical digitizers over CBCT.

The Friedman test yielded qualitative differences among the CBCT system ($\chi^2 = 85.67$, $p < 0.001$). The post-hoc pairwise comparison Nemenyi test identified one device (Carestream) with significantly lower distance to the optically obtained models in comparison to its competitors ($p < 0.05$) with one exception, i.e., the Planmeca CBCT ($p = 0.32$). One

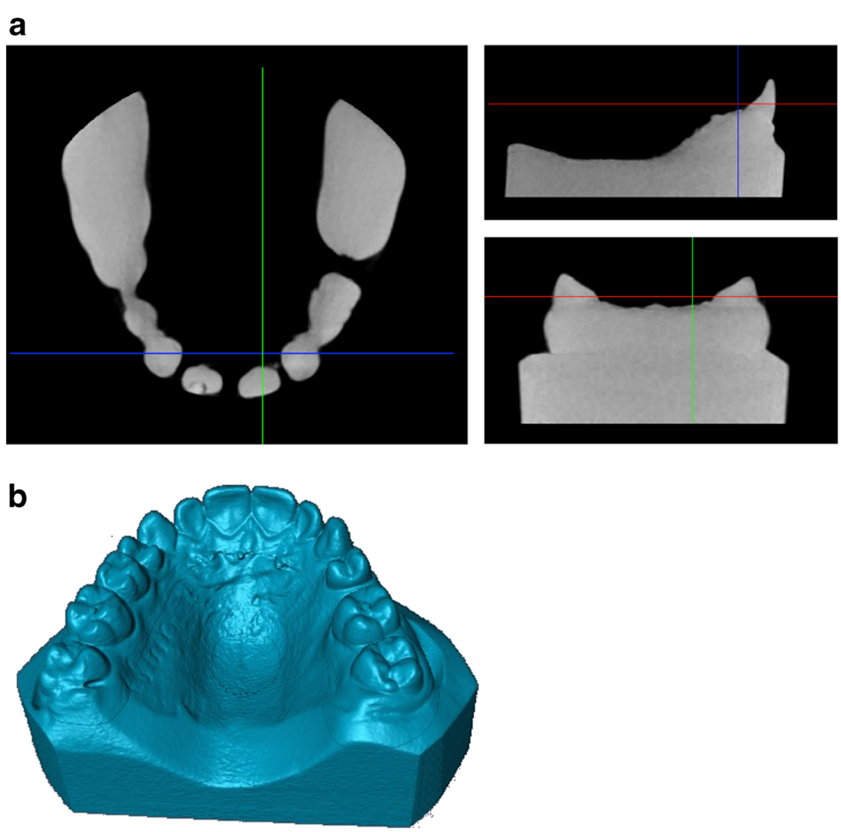

Fig. 2 **a** Slices of a CBCT images from plaster casts in axial, sagittal, and coronal direction, and **b** outcome after segmentation and surface rendering with the Amira software

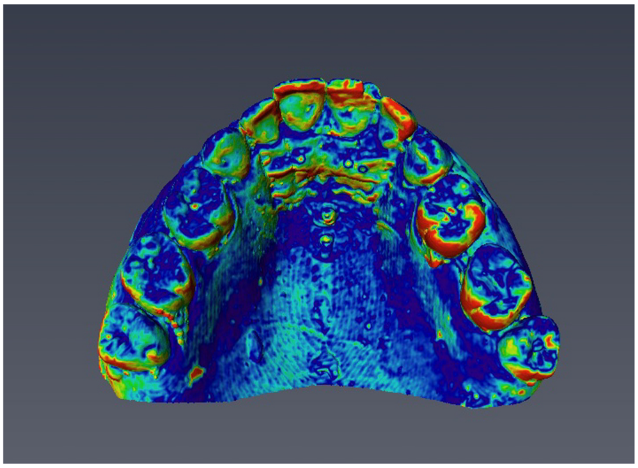

Fig. 3 Heat map colored local surface distances between two corresponding models. (Color convention: blue 0.0 mm, red 1.0 mm distance)

device (eXam) had significantly lower accuracy compared to all other CBCTs ($p < 0.05$), and one system (Planmeca) was significantly better than two of its competitors (Table 3). Hence, hypothesis II stating comparable accuracy among digital models obtained from CBCT had to be rejected, favoring especially one digitizer with dedicated tools for plaster cast digitization (Carestream).

Discussion

The present study aimed to assess whether contemporary CBCT devices are eligible to digitize dental plaster casts for legal storage as well as digital planning purposes. Furthermore, it aimed to assess differences among common CBCT devices and to compare accuracy with optical digitization devices.

Previous research validated geometric accuracy of optical digitizing devices [1, 4–6, 23]. A systematic review evaluated digital data of a dental preparation taken with different optical devices and a reference coordinate measuring machine and found average discrepancies at axial preparation surfaces of 20.8 μm, and of 55.8 μm at occlusal grooves [1]. These findings were confirmed within a recent study, which reported a mean axial preparation surface accuracy of 20.3 μm [4]. The axial values are in-line with the outcomes of the present study, most probably, because most parts of dental models were rather smooth and not undermining or as complex as occlusal grooves.

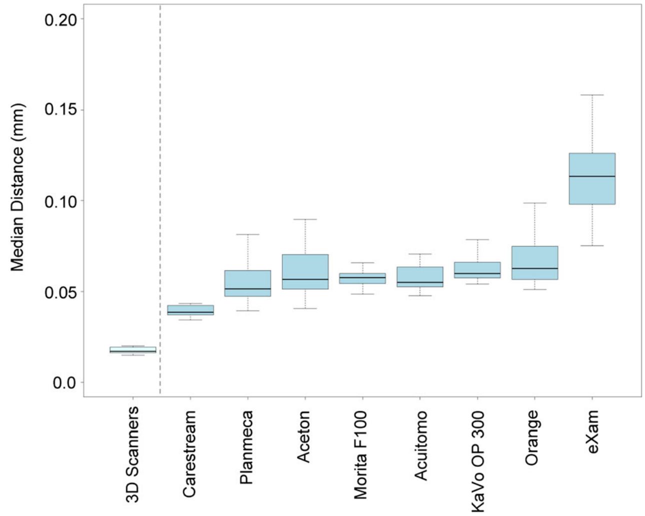

Fig. 4 Boxplot showing the average median surface distances for models digitized with optical scanners and CBCT. The distances between surfaces of plaster models derived from optical devices (left) were assessed in two steps, i.e., pairwise computation of the median distances between all optical scans and computation of the respective mean values for each model. The distances between CBCT and 3D devices (right) were assessed by pairwise computation of the median distance between each surface obtained from CBCT and optical devices, and subsequent calculation of the respective mean values for each model and CBCT system

Whereas usage of CBCT for the digitization of plaster models has been proposed as an alternative to 3D optical digitization [1, 2], best to the knowledge of the authors, no studies assessed and validated geometric accuracy of this procedure until now. Despite, this technology appears promising considering the rising availability of CBCT in dental offices.

Table 3 Outcomes (p values, rounded) from the pairwise comparison post-hoc Nemenyi test

	Accuitomo	Acteon	Carestream	3D exam	R100	OP300	Orange
Acteon	0.943	–	–	–	–	–	–
Carestream	< 0.001*	0.041*	–	–	–	–	–
3D exam	< 0.001*	< 0.001*	< 0.001*	–	–	–	–
R100	0.997	1.0	0.009*	< 0.001*	–	–	–
OP300	0.986	0.438	< 0.001*	0.022*	0.742	–	–
Orange	0.979	0.395	< 0.001*	0.027*	0.701	1.0	–
Planmeca	0.481	0.991	0.316	< 0.001*	0.902	0.072*	0.060

Significances are highlighted with an asterisk (*)

So far, one study digitized ten dried skulls with CBCT, multi-slice CT (MSCT), and optical digitizing devices. To assess accuracy of the different digitization modalities, the distances between each image of the tested devices and reference datasets were obtained. Accuracy from CBCT images (mean error ± standard deviation, 0.34 ± 0.38 mm) was found inferior to MSCT (mean error ± standard deviation, 0.19 ± 0.16 mm), while images from optical devices (mean errors ± standard deviation, 0.10 ± 0.12 mm) were found most accurate [21]. The present study confirmed superiority of optical devices. Despite, median accuracy from optical devices was by factor five higher in the present study, and CBCT devices were up to factor eight more accurate, albeit, accuracy ranges varied considerably from 0.015 mm (Carestream) to 0.0245 mm (Exam) among the CBCT devices.

Another study evaluated the segmentation process for CBCT images of dried human mandibles. The rationale was that threshold determination procedures from different software programs might impact on distance measurements. However, measurements were found reproducible and accurate, and comparable to measurements on the physical models [20]. In the present study, threshold determination was performed in a standardized manner with one software product and a calibrated investigator to minimize bias owing to different segmentation procedures.

Whenever agreement of images from different modalities is to be evaluated, accurate registration is of paramount importance. Otherwise, distance measurements may be altered due to inappropriate alignments. Within a previous study, reproducibility of manual reference point selection on digital casts was investigated and errors in the range of 0.25–0.56 mm were reported [24].

Prior to the present study, we investigated the impact of manual control point selection inaccuracies on the final registration errors. For this purpose, we developed a software program to simulate control point selection errors in the range of 0.2–2.0 mm. The software program performed reference point-based alignments for three up to 15 control points and refined registration using an automated ICP matching algorithm. When reference points had been selected exactly, root mean squared (RMS) errors were below 4.29e-14 and thus negligible. Simulation of reference point selection errors up to 1.0 mm yielded that a minimum of six reference points was needed to achieve accurate control point-based registration, and registration errors again tended to zero following ICP matching [25]. The present study reused the ten casts from this previous investigation for which highly accurate registration had been demonstrated already to minimize potential errors resulting from the alignment procedure.

When accuracies of a new technology are to be evaluated, the new method is usually compared to a gold standard. This allows for using Bland Altman analyses and plotting the true deviation. In the present case, however, several optical digitizers were available on the market, and it is not known if one device is superior to its competitors for all possible plaster models. Due to this, the present study computed the expected median distance (i.e., the mean distance of all observed median distances) among optical scanners and used it as a reference value. In addition, for each model digitized with a CBCT system, the median distances to the respective casts digitized with optical devices were computed, and the expected median distance was again calculated as described above.

Even though it is impossible to assess the true deviation between digital images obtained with a CBCT and an optical scanner, the present method aimed at estimating the most likely distance. Several distance measurements have been performed in the present study: a total of 400 registrations and distance measurements (5 scanners, each compared with 4 other scanners, measurements conducted for 20 different plaster models) were performed to assess the expected median distance among optical scanners, and 800 registrations and distance measurements (8 CBCTs, compared with 5 optical scanners, measurements conducted for 20 models) were performed to estimate the distances among CBCT and optical model scans. Hence, the respective mean values appeared to be eligible to estimate the true distance between images obtained from CBCT and optical digitizers. Despite, a limitation of this method is that it does not account for local deviations, which, however, has not been the goal of the present investigation.

The present study identified significantly higher accuracies for the optical digitizers compared to the CBCT systems. Distances between optically and CBCT digitized models were in the range of 45–60 μm (Fig. 4). Despite of this difference, accuracies of models obtained from CBCT seemed to be sufficient for several clinical purposes including navigated implantology, digital orthodontic planning, and model archiving.

Extra tools for cast digitization as provided by the Carestream company simplified the digitization procedure. These tools might also increase accuracy, since optimized protocols with higher doses can be defined by the manufacturers. In the present study, lowest distances to models obtained from optical devices were observed for models digitized with the CBCT having such a feature. Images from the oldest CBCT (eXam) investigated were significantly inferior to all its competitors, most probably due to technical innovations of the more recent devices.

However, even though it is possible to digitize casts with sufficient quality for several purposes using CBCT from a technical/methodological viewpoint, accuracy is still inferior to optical devices. Thus, at the moment, plaster cast digitization using CBCT will rather be an option for dentists already running a CBCT than replacing optical devices.

In conclusion, contemporary CBCT devices were found to be appropriate for plaster cast digitization. Even though optical devices provided higher resolution, accuracy of models from CBCT appeared to be clinically sufficient for digital dental planning and legal storage requirements. Whereas accuracies were comparable among most CBCT devices, specific tools for cast digitization simplified the process and might increase accuracy, whereas resolution of older devices should be verified carefully prior to clinical usage.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

References

1. De Luca Canto G, Pacheco-Pereira C, Lagravere MO, Flores-Mir C, Major PW (2015) Intra-arch dimensional measurement validity of laser-scanned digital dental models compared with the original plaster models: a systematic review. Orthod Craniofac Res 18(2): 65–76. https://doi.org/10.1111/ocr.12068
2. Abizadeh N, Moles DR, O'Neill J, Noar JH (2012) Digital versus plaster study models: how accurate and reproducible are they? J Orthod 39(3):151–159. https://doi.org/10.1179/1465312512z.00000000023
3. McGuinness NJ, Stephens CD (1992) Storage of orthodontic study models in hospital units in the U.K. Br J Orthod 19(3):227–232. https://doi.org/10.1179/bjo.19.3.227
4. Gonzalez de Villaumbrosia P, Martinez-Rus F, Garcia-Orejas A, Salido MP, Pradies G (2016) In vitro comparison of the accuracy (trueness and precision) of six extraoral dental scanners with different scanning technologies. J Prosthet Dent 116:543–550.e1. https://doi.org/10.1016/j.prosdent.2016.01.025
5. Mandelli F, Gherlone E, Gastaldi G, Ferrari M (2016) Evaluation of the accuracy of extraoral laboratory scanners with a single-tooth abutment model: a 3D analysis. J Prosthod Res 61(4):363–370. https://doi.org/10.1016/j.jpor.2016.09.002
6. Patzelt SB, Emmanouilidi A, Stampf S, Strub JR, Att W (2014) Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig 18(6):1687–1694. https://doi.org/10.1007/s00784-013-1132-y
7. Widmann G, Bale RJ (2006) Accuracy in computer-aided implant surgery—a review. Int J Oral Maxillofac Implants 21(2):305–313
8. Behneke A, Burwinkel M, Knierim K, Behneke N (2012) Accuracy assessment of cone beam computed tomography-derived laboratory-based surgical templates on partially edentulous patients. Clin Oral Implants Res 23(2):137–143. https://doi.org/10.1111/j.1600-0501.2011.02176.x
9. Vermeulen J (2016) The accuracy of implant placement by experienced surgeons: guided vs freehand approach in a simulated plastic model. Int J Oral Maxillofac Implants. 10.11607/jomi.5065
10. Van Assche N, Vercruyssen M, Coucke W, Teughels W, Jacobs R, Quirynen M (2012) Accuracy of computer-aided implant placement. Clin Oral Implants Res 23:112–123. https://doi.org/10.1111/j.1600-0501.2012.02552.x
11. Jung RE, Schneider D, Ganeles J, Wismeijer D, Zwahlen M, Hammerle CH, Tahmaseb A (2009) Computer technology applications in surgical implant dentistry: a systematic review. Int J Oral Maxillofac Implants 24(Suppl):92–109
12. Martorelli M, Gerbino S, Giudice M, Ausiello P (2013) A comparison between customized clear and removable orthodontic appliances manufactured using RP and CNC techniques. Dent Mater 29(2):e1–e10. https://doi.org/10.1016/j.dental.2012.10.011
13. Saxe AK, Louie LJ, Mah J (2010) Efficiency and effectiveness of SureSmile. World J Orthod 11(1):16–22
14. Sachdeva RC, Aranha SL, Egan ME, Gross HT, Sachdeva NS, Currier GF, Kadioglu O (2012) Treatment time: SureSmile vs conventional. Orthodontics 13(1):72–85
15. Segal GR, Schiffman PH, Tuncay OC (2004) Meta analysis of the treatment-related factors of external apical root resorption. Orthod Craniofac Res 7(2):71–78. https://doi.org/10.1111/j.1601-6343.2004.00286.x
16. Maino BG, Paoletto E, Lombardo L 3rd, Siciliani G (2016) A three-dimensional digital insertion guide for palatal miniscrew placement. J Clin Orthod 50(1):12–22
17. Barreto MS, Faber J, Vogel CJ, Araujo TM (2016) Reliability of digital orthodontic setups. Angle Orthod 86(2):255–259. https://doi.org/10.2319/120914-890.1
18. Choi DS, Jeong YM, Jang I, Jost-Brinkmann PG, Cha BK (2010) Accuracy and reliability of palatal superimposition of three-dimensional digital models. Angle Orthod 80(4):497–503. https://doi.org/10.2319/101309-569.1
19. Krieger E, Seiferth J, Saric I, Jung BA, Wehrbein H (2011) Accuracy of Invisalign(R) treatments in the anterior tooth region. First results. J Orofac Orthop 72(2):141–149. https://doi.org/10.1007/s00056-011-0017-4
20. Poleti ML, Fernandes TM, Pagin O, Moretti MR, Rubira-Bullen IR (2016) Analysis of linear measurements on 3D surface models using CBCT data segmentation obtained by automatic standard pre-set thresholds in two segmentation software programs: an in vitro study. Clin Oral Investig 20(1):179–185. https://doi.org/10.1007/s00784-015-1485-5
21. Kang S-H, Kim Y-H, Kim M-K (2016) Comparison of digital dental images yielded by digital dental casts, cone-beam computed tomography, and multislice computed tomography for measurement of dental area. Oral Radiol 33(1):1–9. https://doi.org/10.1007/s11282-016-0242-z
22. Core Team R (2016) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna https://www.R-project.org/
23. Reuschl RP, Heuer W, Stiesch M, Wenzel D, Dittmer MP (2016) Reliability and validity of measurements on digital study models and plaster models. Eur J Orthod 38(1):22–26. https://doi.org/10.1093/ejo/cjv001
24. Ashmore JL, Kurland BF, King GJ, Wheeler TT, Ghafari J, Ramsay DS (2002) A 3-dimensional analysis of molar movement during headgear treatment. Am J Orthod Dentofac Orthop 121(1):18–29; discussion 29-30. https://doi.org/10.1067/mod.2002.120687
25. Becker K, Wilmes B, Grandjean C, Drescher D (2017) Impact of manual control point selection accuracy on automated surface matching of digital dental models. Clin Oral Investig. https://doi.org/10.1007/s00784-017-2155-6