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REVIEW ARTICLE

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Intra-arch dimensional measurement validity of laser-scanned digital dental models compared with the original plaster models: a systematic review

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Abstract

A systematic review was undertaken to evaluate the validity of intra-arch dimensional measurements made from laser-scanned digital dental models in comparison with measurements directly obtained from the original plaster casts (gold standard). Finally included articles were only those reporting studies that compared measurements from digital models produced from laser scanning against their plaster models. Measurements from the original plaster models should have been made using a manual or digital caliper (gold standard). Articles that used scans from impressions or digital photographs were discarded. Detailed individual search strategies for Cochrane, EMBASE, MEDLINE, PubMed, and LILACS were developed. The references cited in the selected articles were also checked for any references that could have been missed in the electronic database searches. A partial gray literature search was undertaken using Google Scholar. The methodology of selected studies was evaluated using the 14-item quality assessment tool for diagnostic accuracy studies (QUADAS). Only 16 studies were finally included for the qualitative/quantitative synthesis. The selected studies consistently agree that the validity of measurements obtained after using a laser scanner from plaster models is similar to direct measurements. Any stated differences would be unlikely clinically relevant. There is consistent scientific evidence to support the validity of measurements from digital dental models in comparison with intra-arch dimensional measurements directly obtained from them.

Key words: digital model; laser scanning; plaster model; systematic review; validity

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Introduction

In dentistry, plaster models play an important role in pre-, during, and post-treatment evaluation of occlusal relationships. Dental models act as an auxiliary diagnostic tool for the clinician as well as providing a record of treatment outcomes (1). Additionally, study models are important for didactic and research purposes, assessment of treatment progress, and case documentation (2). The use of plaster models is widespread but is linked to several problems, mainly breakage, loss, and storage requirements (1). The need to retain dental casts for legal documentation has created long-term storage problems among dentists (3).

The space required for storage of traditional models for every one thousand patients is up to 17 m^3 (3). This storage requirement is associated with a significant cost. A more convenient and cost-effective means for recording and storing while maintaining accurate records is needed (4). This quest has encouraged research on alternative storage methods. These efforts include photocopy, holography, stereophotogrammetry, photography, digitized study models, and CT scanning (1).

Digital storage eliminates inherent problems related to physical storage of models (3). It is especially important in orthodontic environments due to the volume of plaster models generated. The replacement of plaster orthodontic models with virtual information has further potential benefits including the following: (1) instant accessibility of 3D information without need for retrieval of plaster models from a storage area; (2) the ability to perform electronically accurate and simple diagnostic setups of various extraction patterns; (3) virtual images may be transferred to other formats for instant referral or consultation; and (4) objective model grading system analysis (5).

Previous systematic reviews (5, 6) have evaluated the accuracy of digital models comparing them to plaster models. As they included articles that used scans from impressions or photographs of models, they did not specifically assess the validity of scans taken from plaster study models. Furthermore, we have identified that some potentially pertinent studies (1, 7–14) were not included in these previous systematic reviews.

The purpose of this systematic review was to focus on the validity of measurements made from laser-scanned digital models obtained from plaster models in comparison with actual measurements directly obtained from the same physical dental casts (gold standard). This very focused goal should be of clinical interest when a significant number of plaster models are available from cases already completed. In this scenario, directly scanning the teeth in the mouth is not an option. If this laser scanning demonstrates to be valid, then the original casts could be disposed with the concurrent saving in space and resources.

Methods

We conducted this systematic review adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (15) Checklist.

Protocol registration

We did not register the systematic review protocol. No systematic review protocol was available.

Study design

We did a systematic review of studies that compared the validity of digital dental models produced from laser scanning against measurements from the original physical dental models.

Eligibility criteria

We retained only articles that compared digital models produced from laser scanning of plaster dental models (gold standard) with the original plaster model. Measurements from the plaster models should have been performed using a manual or digital caliper. We discarded articles that used scans from impressions or digital photographs. We considered studies from any language or peer-reviewed source. We did not include reviews, letters, and personal opinions.

Information sources

We developed detailed individual search strategies for each of the following bibliographic databases: Cochrane, EMBASE, MEDLINE, PubMed, and LILACS. References cited in the finally selected articles for any references were also hand searched for articles that could have been missed during the electronic database searches. We did a partial gray literature search using Google Scholar. This search was limited to the first 100 most relevant articles.

Search

Appropriate truncation and word combinations were selected and adapted for each database search (Appendix S1). We managed all references by reference manager software (RefWorks-COS, ProQuest, LLC. Bethesda, MD, USA), and duplicate hits were removed. The end search date was December 11, 2013 and the update was May 7, 2014, across all databases.

Study selection

We completed the selection in two phases. In phase 1, two reviewers independently reviewed the titles and abstracts of all identified electronic database citations. Studies that appeared not to fulfill the inclusion criteria were discarded. In phase 2, the same selection criteria were applied to the full articles to confirm their eligibility. This additional step was necessary as some abstracts may have been misleading by representing study details incorrectly or partially. The same two reviewers independently participated in phase 2. Any disagreement in either phase was discussed by both reviewers. A third author was involved when required to make a final decision.

Data collection process

Two authors collected the required information from the selected articles, after which cross-checking procedures ascertained the completeness and precision of the retrieved information.

Data items

For the included studies, we recorded the following information: author, year of publication, country, sample size, study objectives, methods, results, and conclusions pertaining to the comparison between digital dental models and physical dental models. If the required data were not available in the article, attempts were made to contact the authors to retrieve any missing information.

Risk of bias in individual studies

The methodology of selected studies was evaluated using the 14-item quality assessment tool for diagnostic accuracy studies (QUADAS) (16). Two reviewers scored each item as ‘yes,’ ‘no,’ or ‘unclear’ and assessed independently the quality of each included study. Disagreement between both reviewers was solved by a third reviewer.

Summary measures

We considered any type of outcome measurement (continuous variables - mean difference, range, ratio, and *p* value).

Synthesis of results

We planned a meta-analysis if the data from different studies were relatively homogeneous.

Results

Study selection

During the initial search, 569 citations across the five electronic databases were identified. The duplicates were removed and 292 citations remained. After an evaluation of the information provided from the abstracts, 260 were later excluded. Therefore, only 34 abstracts were finally selected for phase 2 assessments. In addition, five studies were selected from Google

Scholar. (12–14, 17, 18) To complete the process, we identified two additional studies (19, 20) from reviewing the reference cited by these 39 studies available at this selection stage. Thus, we reviewed the full text in 41 studies. Once full copies of the articles of these abstracts were obtained, 25 were later excluded. A list and reasons for exclusion of those articles can be obtained directly from the authors.

Finally, the selection criteria enabled retention of only 16 studies (1, 4, 7–14, 17–22) for the qualitative/quantitative synthesis. A flow chart of the process of identification, inclusion, and exclusion of studies is shown in Fig. 1.

Study characteristics

The selected studies were conducted in seven different countries: Australia (19), Brazil (9, 11, 14, 20), Canada (13, 17), Israel (22), Japan (10, 12), United Kingdom (1, 4, 21), and USA (7, 8, 18). The sample size ranged from one to 112 plaster models. A summary of the study descriptive characteristics can be found in Table 1. The gold standard in all selected studies was through the use of a digital caliper (precision = 0.01 mm) measuring plaster models.

Risk of bias within studies

The overall percentage of the QUADAS criteria for each study is provided in Appendix S2. The QUADAS criteria ranged from 34% to 78%. The main methodological limitations were related to item ‘results interpreted without knowledge of results of the reference standard’ and ‘reference standard results interpreted without knowledge of index.’ Two domains were unclear in all selected studies (‘index test results interpreted without knowledge of results of the reference standard’ and ‘reference standard results interpreted without knowledge of index test’).

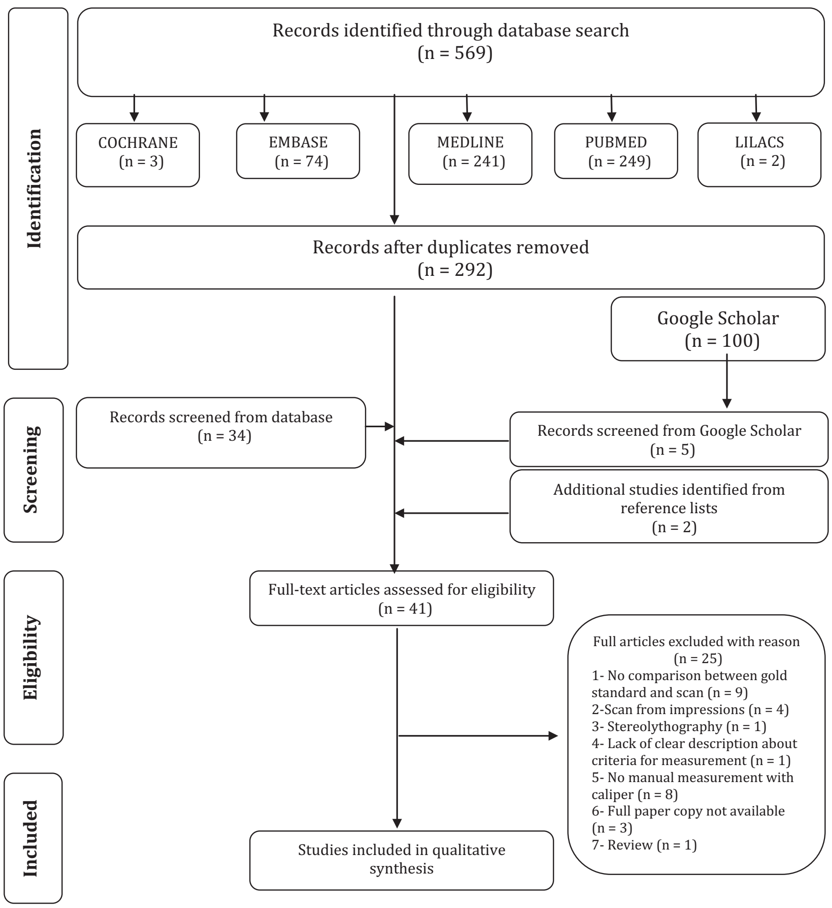

Fig. 1. Flow diagram of literature search and selection criteria. Adapted from PRISMA.

Table 1. **Summary of descriptive characteristics of included articles**

Author, year	Country	Sample size	Objectives	Method	Scan device and software	Main conclusion
Abizadeh et al. 2012 (1)	UK	112 sets of PM	To compare measurements of occlusal relationships and arch dimensions taken from DM and PM	Single examiner, 10 models measured at a time	R250 Scanner, (3-Shape™, Copenhagen, Denmark) ESM Digital Solutions software	Differences between measurements taken from PM and from DM were not clinically relevant
Akyalcin et al. 2013 (7)	USA	30 sets of PM	To assess diagnostic accuracy and surface matching characteristics of 3D DM obtained from various sources	Two examiners, second measurement made 3 to 4 weeks later	Ortho Insight 3D laser scanner (Motionview Software, Hixson, Tenn, USA) Digital models–emodel system (GeoDigm, Chanhassen, Minn, USA).	A strong surface match correlation was observed between the virtual scanned models and the emodels, indicating that these could be used interchangeably
Asquith et al. 2007 (4)	UK	10 sets of PM	To compare measurements made on PM with those on DM	Two examiners measured independently	Arius3D Foundation System Scan (Initition, London, UK) Pointstream 3D image suite (Windows application)	Measurements were not clinically significant different between PM and DM.
Goonewarden et al. 2008 (19)	Australia	50 sets of PM	To compare measurements made on PM with those on DM	Single examiner, second measurement 2 weeks later for 10 sets of randomly selected models	Orthocad Scanning and software (Cadent Inc., Fairview, NJ, USA)	Accurate and valid irregularity index measurements from DM. Significant differences between manual and digital measurements, but differences were not clinically significant.

***Table 1.* (continued)**

Author, year	Country	Sample size	Objectives	Method	Scan device and software	Main conclusion
Grünheid et al. 2014 (8)	USA	30 sets of PM	To assess accuracy, reproducibility, and time efficiency of dental measurements taken on 3 types of DM	Three examiners; second measurement in 6 sets randomly selected 3 weeks later	eModel, version 6.0 (GeoDigm Corp., Chanhassen, Minn, USA).	Tooth width measurements on DM can be as accurate as and might be more reproducible and significantly faster than those taken on PM. Of the models studied, the SureSmile models provided the best combination of accuracy, reproducibility, and time efficiency of measurement
Horton et al. 2010 (18)	USA	32 sets of PM	To identify the DM measurement technique for tooth width yielding the best combination of speed, accuracy, and precision	Single examiner, 3 sets of measurements for each cast	Geodigm	Strong correlation between digital and manual measurements. Digital measurements are an appropriate method for determining tooth width
Kaihara et al. 2013 (12)	Japan	1 set of PM	To assess accuracy of DM compared to PM	Three examiners independently, 10 times	RexcanDS (Solutionix, Seoul, Korea). RapidForm 2006 software (INUS Technology Inc., Seoul, South Korea)	No clinical significant difference for any of the tooth width or arch dimension measurements. The accuracy of analyzing the dentition using a 3D scanner is similar to PM

***Table 1.* (continued)**

Author, year	Country	Sample size	Objectives	Method	Scan device and software	Main conclusion
Keating et al. 2008 (21)	UK	30 sets of PM	To evaluate accuracy and reproducibility of 3D optical laser scanning to record PM surface detail. To evaluate accuracy of PM constructed from digital files.	Single examiner. 2 times, 1 week apart	VIVID 900 (Minolta Inc., Tokyo, Japan) RapidForm software (INUS Technology Inc., Seoul, Korea) SLA-250/40 (3D Systems Inc.,Valencia, CA, USA)	3D DM are an accurate representation of PM. The accuracy and detail of RP reconstructed models may not be sufficient for certain applications
Kim et al. 2014 (13)	Canada	60 sets of PM	To compare accuracy of tooth width and arch measurements obtained from 3D laser scans to those obtained from PM and CBCT patient scans	Single examiner. Same day	The Ortho Insight (Motionview Software LLC, Hixson, Tenn, USA)	Laser-scanned models are highly accurate compared to PM
Oliveira et al. 2007 (9)	Brazil	6 sets of PM	To compare reliability of DM and PM as a diagnostic aid.	Three examiners independently. Three times each cast	eModel (Geodigm Corp., Minnesota, USA)	Digital dental casts are as reliable as PM for orthodontic treatment planning
Redlich et al. 2008 (22)	Israel	30 PM	To assess accuracy of DM measurements from PM	Not reported	Conoprobe (Optimet, Jerusalem, Israel) 3D TELEDENT custom-made software	Accuracy of technique of cross-sectional planes measurements of 3D-scanned models does not differ from manual caliper measurement of casts. Linear measurements may cause clinical inaccuracy when calculating space analysis in a crowded dentition.

***Table 1.* (continued)**

Author, year	Country	Sample size	Objectives	Method	Scan device and software	Main conclusion
Sanches et al. 2013 (14)	Brazil	30 PM	To compare measurements of PM and DM and assess their application in Tanaka and Johnson regression equation for predicting crowding	# of examiners not stated All measurements were repeated after 1 week	R-700 Orthodontic 3D Scanner (Copenhagen, Denmark). O3d software (Widialabs, Goiânia, Brazil)	Dental size measurements showed good reproducibility in both PM and DM.
Sohmura et al. 2004 (10)	Japan	Simple gypsum cuboid block and one PM	To examine potential and accuracy of multi-slice medical CT and laser scanner for conventional dental cast measurements	Not reported	Multi-slice helical CT, SOMATOM Sensational16 (Siemens AG, Munich, Germany) VIVID 700 and VIVID 910 laser scanner (Minolta, Osaka, Japan). FreeForm V6.0 and PHANToM Desktop (SensAble Technologies, Woburn, USA).	The morphology of CT images was slightly inferior to laser scans. CT allowed visualization of undercut areas not imaged with laser
Sousa et al. 2012 (11)	Brazil	20 PM	To determine accuracy and reproducibility of dental arch measurements from DM compared PM	Two examiners. Enlargement of digital images to facilitate measurements	3Shape scanner (D-250; 3Shape, Copenhagen, Denmark) 3D images analyzed using Geomatic studio 5 software, (Raindrop Geomatic Inc., Morrisville, NC, USA)	The reproducibility of DM was similar to direct caliper measurements on the PM. Measurements of arch width and length on DM showed high accuracy. DM can be used for storing purposes and for research with satisfactory degrees of accuracy and reproducibility

***Table 1.* (continued)**

Author, year	Country	Sample size	Objectives	Method	Scan device and software	Main conclusion
Stevens et al. 2006 (17)	Canada	24 sets of PM	To compare PM and DM measurements	Three examiners independently 3 times and once measurements by each secondary examiner	GeoDigm version 6, eModels software (GeoDigm, Chanhassen, Minn. USA)	DM are clinically acceptable replacement for PM for the routine measurements made in orthodontic practices. DM are not a compromised choice for treatment planning and diagnosis. DM are clinically valid for measurement of Bolton, PAR, and their constituents.
Watanabe-Kanno et al. 2009 (20)	Brazil	15 sets of PM	To determine reproducibility, reliability, and validity of measurements in DM compared to PM.	Two examiners, each repeating the measurements 3 times.	CT Scanned by Bibliocast Company (France), Cécile3 version 2.554.2 beta software.	Measurements from DM compared to PM could be considered clinically acceptable

3D = three dimensional.
ANOVA = One-way analysis of variance.
DM = digital model.
ICC = intraclass correlation coefficient.
PM = plastic model.
RP = Rapid Prototyping.
SD = standard deviation.

Synthesis of results

As the data from the included studies were significantly heterogeneous, a meta-analysis was not justified. Therefore, only a qualitative synthesis is provided. Akyalcin et al. (7) found that both the intra-observer repeatability and the reproducibility of the observers showed near perfect agreement (ICCs >0.92) for the arch length discrepancy measurements.

Most articles (1, 8, 10–14, 17–22) reported statistically significant differences ($p < 0.05$) in tooth width measurements between digital and plaster model measurement methods. Asquith et al. (4) reported statistically significant differences for 4 of 11 dental arch linear measurements between plaster and digital. They reported a 4.7 mm greater mean difference in maxillary arch length with digital measurement. This magnitude of difference was unique to this study and was related to a particular technique for measuring arch length. All other studies reporting arch dimension mean differences (including arch length) all being <1.2 mm (1).

Some differences of special clinical interest were as follows: Transverse arch dimension mean differences were all <0.38 mm (4). Only one study reported overjet measurements being significantly different with a mean difference of 0.31 mm (20). Mean difference in overbite was reported to be significantly different (0.22–0.67 mm) (1, 17, 20). Complementary information can be found in Appendix S3.

Discussion

Plaster models in dentistry and particularly in orthodontics are a necessary diagnostic tool. In orthodontics, measurements typically include tooth dimensions (mesial–distal width), arch dimensions (arch length, intercanine width, interpremolar width, intermolar width), overbite, overjet, centerline relationship, anteroposterior occlusal relationship (Angle's Classification), transverse interarch relationships (x-bites), and buccal-lingual discrepancy between adjacent tooth contact areas. These measurements can be used to calculate estimates of dental crowding and interarch relationships such as Bolton ratios. All 16 studies included in this systematic review (1, 4, 7–12, 14, 17–23) concluded that precision and accuracy (reliability and validity) of digital models obtained by scanning plaster models are clinically acceptable as a diagnostic tool (17).

The term 'reliability' describes the overall consistency of a measurement under constant conditions (17). Reproducibility describes the degree of agreement conducted on replicate specimens and implies replication of the entire experiment to acquire multiple measurements. Validity describes the degree to which a measurement represents what you want to measure. The degree of reliability and accuracy required depends on the nature of decisions being made (17).

The degree of accuracy required for any measurement tool needs to be considered based on the intended application. In the case of comparing a new diagnostic treatment planning tool against an existing gold standard, the assumption is often made that the existing tool is highly accurate. It is well accepted that plaster dental study models provide a suitable physical representation of the patient's dental arch. Sufficient evidence to support this assumption is provided by the fact that plaster models are effectively used to fabricate a variety of dental appliances that fit adequately on the teeth. However, caliper measurements taken from plaster models do have intra-examiner and interexaminer repeated measurements random errors. When considering if laser-scanned copies of plaster study models are an appropriate substitute for the original plaster model, both the random error associated with repeated digital measurement and systematic error resulting from the laser scanning process need to be considered. If the sum of these errors is large enough, they can be clinically significant.

For the purposes of orthodontic treatment planning, tooth width measurements are used to evaluate severity of crowding and Bolton ratios. Because random errors in measuring tooth width will be both positive and negative, over a series of measurements, they become less important (17). It is unlikely that differences in individual tooth width measurements <0.5 mm are clinically significant (20). Bolton ratios with differences <1 mm do not alter treatment planning and crowding estimates that vary <1 mm are very unlikely to change a treatment plan decision from extraction to non-extraction. Stevens et al. (17) suggested that the slight differences in overbite and overjet were most likely related to the bulkiness of the caliper and although the digital measurements were more accurate, the difference was not clinically relevant (17).

The main objective of this systematic review was to focus on the evaluation of the validity of measurements made from laser-scanned digital models in comparison with actual measurements directly obtained from their plaster models. The present systematic review provides very strong evidence that laser scanning of previously obtained plaster study models is an appropriate alternative to maintaining plaster models long term as the measurement precision in the new format is maintained.

Limitations

Some methodological limitations of this review should be considered. First, there was no standardization regarding the methodology. Second, there was a big size range between the evaluated samples. One article (12) had only one pair of models, another had six models (9), one (10) analyzed a gypsum cuboid block and one model, and another (1) had 112 plaster models. Consideration was not given to other diagnostic processes conducted with plaster models outside of intra-arch dimensional measurements.

Conclusion

All of the included studies demonstrated that with some minor differences, both laser-scanned digital and plaster model measurements are valid.

Clinical relevance

The present systematic review provides very strong evidence that laser scanning of previously obtained plaster study models is an appropriate alternative to maintaining plaster models long term as the original dimensions in the new format are maintained. Consideration was not given to other diagnostic processes conducted with plaster models outside of intra-arch dimensional measurements.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. List of search terms

Appendix S2. Summary of descriptive characteristics of included articles

Appendix S3. Quality assessment of included studies