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Accuracy, reproducibility, and time efficiency of dental measurements using different technologies

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Introduction: Historically, orthodontists have taken dental measurements on plaster models. Technological advances now allow orthodontists to take these measurements on digital models. In this study, we aimed to assess the accuracy, reproducibility, and time efficiency of dental measurements taken on 3 types of digital models. **Methods:** emodels (GeoDigm, Falcon Heights, Minn), SureSmile models (OraMetrix, Richardson, Tex), and AnatoModels (Anatomage, San Jose, Calif) were made for 30 patients. Mesiodistal tooth-width measurements taken on these digital models were timed and compared with those on the corresponding plaster models, which were used as the gold standard. Accuracy and reproducibility were assessed using the Bland-Altman method. Differences in time efficiency were tested for statistical significance with 1-way analysis of variance. **Results:** Measurements on SureSmile models were the most accurate, followed by those on emodels and AnatoModels. Measurements taken on SureSmile models were also the most reproducible. Measurements taken on SureSmile models and emodels were significantly faster than those taken on AnatoModels and plaster models. **Conclusions:** Tooth-width measurements on digital models can be as accurate as, and might be more reproducible and significantly faster than, those taken on plaster models. Of the models studied, the SureSmile models provided the best combination of accuracy, reproducibility, and time efficiency of measurement. (Am J Orthod Dentofacial Orthop 2014;145:157-64)

Dental models provide a 3-dimensional view of a patient's occlusion; this enables the clinician to evaluate the malocclusion in more detail than by a clinical examination. In orthodontics, measurements made on dental models are an integral part of the armamentarium used for diagnosis and treatment planning. In fact, dental models have been reported to be the major record used for orthodontic treatment planning.[1]

Historically, orthodontists have used dental models made from plaster. With proper impression and pour-up techniques, these models provide an accurate representation of a patient's dentition and surrounding structures.[2-4] However, plaster models have limitations: they are at risk for breakage, chipping, or abrasion and create the need for storage rooms and their associated expenses.[2,5] Technological advances have allowed orthodontists to perform measurements on digital models, which alleviate many of the obstacles encountered with plaster models. Digital models are not subject to physical damage or degradation, the digital file can be easily transferred to other clinicians or retrieved at multiple locations, and digital storage eliminates problems related to physical storage of traditional plaster models.[6,7]

As a result of these advantages and their increasing affordability, more orthodontists are incorporating digital models into their practices.[8,9] Currently, most digital models are made from alginate impressions, which are either scanned directly or poured in plaster and then

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scanned. With the increased use of cone-beam computed tomography (CBCT) in orthodontics, several companies have introduced another method of digital model fabrication. Sophisticated software algorithms now allow digital model fabrication from a patient's CBCT scan; this eliminates the need for traditional impressions altogether.[5,9]

Obviously, the potential advantages of digital models would be negated if the accuracy and efficiency of their measurements were not comparable with those taken on plaster models, the current gold standard with a long and proven history in orthodontics.[2-4] Since many types of digital models are marketed to orthodontists today, these models need to be evaluated in the practice of evidence-based clinical orthodontics. The aims of this study were, therefore, to compare the accuracy, reproducibility, and time efficiency of dental measurements taken on 3 types of digital models with those taken on traditional plaster models, and to determine the model type that yields the best combination of accuracy, reproducibility, and time efficiency of measurement. Specifically, the digital models studied were emodels (GeoDigm, Falcon Heights, Minn), SureSmile models (OraMetrix, Richardson, Tex), and AnatoModels (Anatomage, San Jose, Calif).

MATERIAL AND METHODS

The pretreatment models of 30 consecutive patients were used for this study. The patients had a variety of typical malocclusions and fully erupted permanent dentitions including incisors, canines, premolars, and first molars. Each patient had alginate impressions, a wax bite registration, and a CBCT scan taken as part of the diagnostic records. The CBCT scans were full field of view scans with a Next Generation i-CAT (Imaging Sciences International, Hatfield, Pa) at a voxel size of 0.3 mm^3 and a scan time of 8.9 seconds.

Plaster models were fabricated by pouring the alginate impressions in type II dental plaster (Modern Materials Orthodontic Plaster; Heraeus Kulzer, South Bend, Ind). emodels were then fabricated from these plaster models by GeoDigm. SureSmile models were fabricated by OraMetrix from CBCT scans of the plaster models taken with the Next Generation i-CAT at a voxel size of 0.2 mm^3, a scan time of 26.9 seconds, and a wax-bite registration separating the maxillary and mandibular models to allow segmentation of the teeth. The plaster model, emodel, and SureSmile model of each patient were thus made from the same impressions and should have yielded identical measurements. AnatoModels were produced by Anatomage from the CBCT scan that had been taken as part of each patient's diagnostic records. All models were deidentified before the study. The use of deidentified models had been approved by the institutional review board at the University of Minnesota.

Three calibrated operators (T.G., N.P., N.L.D.F.) measured the widths of the each tooth mesial to the second molars as the greatest mesiodistal diameter of their crowns as required for Bolton's tooth-size analysis.[10,11] In addition to their previous experience in the use of the types of dental models studied, the operators each measured 5 practice cases before data collection.

The measurements on the plaster models were taken manually using digital calipers (Ortho Organizers, Carlsbad, Calif), whereas those on the digital models were taken on a 22-in computer monitor (XPS; Dell, Round Rock, Tex) with landscape orientation at a screen resolution of 1680 × 1080 pixels using the software tools from the respective manufacturers (Table 1). Measurements were taken to the nearest 0.01 mm on the plaster models, emodels, and AnatoModels, and to the nearest 0.1 mm on the SureSmile models because this is the smallest unit that can be measured with the SureSmile software. Examples of measurements with the various methods are shown in Figure 1.

The 3 operators completed the measurements on all 30 models of 1 type before proceeding to the next model type. In each model type, the sequence in which the models were measured was randomized for each operator. Each set of measurements was timed to the nearest second using a digital stopwatch. For all models, the time was started when the models were in front of the operator, ready for analysis, and stopped when all measurements had been completed (Table 1). After a washout period of 3 weeks, 6 cases were randomly selected from the original 30 and remeasured by all operators to assess within-rater repeatability.

Statistical analyses

Accuracy was assessed, separately for each type of digital model, as the degree of agreement between the measurements on the digital models and those on the corresponding plaster model using the method of Bland and Altman.[12,13] To account for the correlation between tooth widths in a patient and to avoid underestimation of the variance, a mixed model with a random intercept term (for person) was used to obtain the variance estimates used in the Bland-Altman analysis.[14] Bias was computed, separately for each type of digital model, as the average of the differences between the digital model measurements and the plaster model measurements for each tooth. Calculation of the limits of agreement during the Bland-Altman analysis provided limits that contained 95% of the differences for each

Table I. Comparison of the methods used to perform tooth-width measurements on the model types studied

	Plaster model	*emodel*	*SureSmile model*	*AnatoModel*
Model retrieval	Storage room	Server	Server	Server
Measuring tool	Digital calipers (calibrated between each set of models)	emodel software version 9.0 (GeoDigm)	SureSmile software version 5.9 (OraMetrix)	AnatoModel software version 5.0 (Anatomage)
Model manipulation	By hand	Virtual rotation and magnification	Virtual rotation and magnification	Virtual rotation and magnification
Software manipulation used to measure	NA	Analysis feature	Diagnostic model and new treatment simulation features	Occlusal layout feature with both arches visible
Selection of measuring points	By operator	By operator	By SureSmile technician; modified by operator	By operator
Time started	Models in front of operator	Models on computer screen	Models on computer screen	Models on computer screen
Time stopped	After recording all measurements	After completing measurements on computer	After completing measurements on computer	After completing measurements on computer
Measurements recorded	With pencil on a sheet of paper	On computer hard drive as an EMZ file	On SureSmile server	On computer hard drive as a JPEG file

NA, Not applicable.

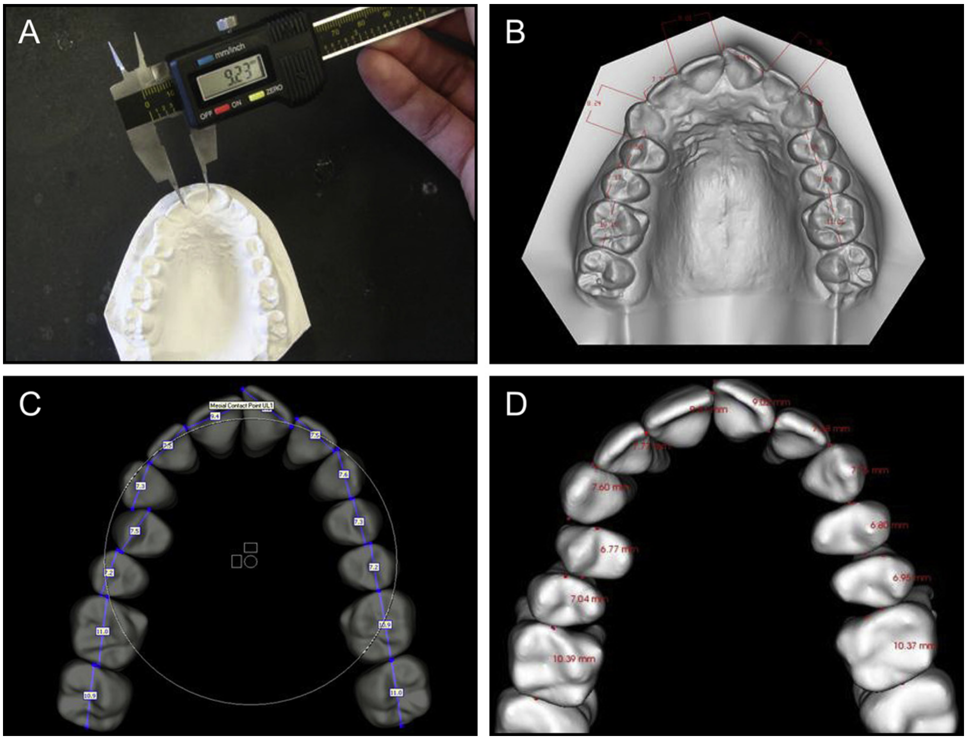

Fig 1. Examples of tooth-width measurements taken on the 4 types of dental models studied: **A,** plaster model; **B,** emodel; **C,** SureSmile model; **D,** AnatoModel.

type of digital model. When ranking the measurements on accuracy, both the bias and the variance were taken into account by calculating the mean squared error: mean squared error $=$ bias^2 $+$ variance.

Reproducibility, or between-rater reproducibility, was assessed as the degree of agreement between the measurements performed on replicate specimens by the 3 operators using the Bland-Altman method.[15] The

Table II. Repeatability comparison of tooth-width measurements

Model	*Bias (mm)*	*Lower limit of agreement (mm)*	*Upper limit of agreement (mm)*	*Limit of agreement interval width (mm)*	*Mean squared error*
Plaster model	0.048	−0.304	0.400	0.704	0.035
emodel	−0.028	−0.410	0.355	0.765	0.039
SureSmile model	−0.011	−0.231	0.209	0.440	0.013
AnatoModel	0.006	−0.487	0.500	0.987	0.063

Table III. Accuracy comparison of tooth-width measurements

Model	*Bias (mm)*	*Lower limit of agreement (mm)*	*Upper limit of agreement (mm)*	*Limit of agreement interval width (mm)*	*Mean squared error*
emodel	0.285	−0.176	0.746	0.922	0.134
SureSmile model	−0.130	−0.604	0.344	0.947	0.073
AnatoModel	0.191	−0.57	0.952	1.521	0.181

mean squared error was calculated to rank the measurements of reproducibility as detailed above.

Repeatability was assessed as the degree of agreement of measurements on the replicate specimens within each operator using the Bland-Altman method.[15] Again, the mean squared error was calculated to rank the methods.

Time efficiency was assessed as the time required for measuring all tooth widths on the various model types. Mean values and standard deviations of the time required were calculated for each model type, and differences among the model types were tested for statistical significance using 1-way analysis of variance with the Tukey method as a post-hoc pairwise comparison after it had been confirmed that the data conformed to assumptions underlying parametric statistics (Kolmogorov-Smirnov test).

All statistical analyses were performed using R Statistical Software (version 2.9.2; R Foundation for Statistical Computing, Vienna, Austria), with *P* values of less than 0.05 considered statistically significant.

RESULTS

Repeatability comparisons of individual tooth-width measurements are reported in Table II. On average, the measurements were repeatable to 0.05 mm for each type of dental model.

Accuracy comparisons of the tooth-width measurements are reported in Table III. The accuracy, as assessed by the mean squared error, was best for the measurements taken on the SureSmile models, followed by those on the emodels. The measurements on the AnatoModels were the least accurate. The Bland-Altman plots of tooth widths are shown in Figure 2.

Reproducibility comparisons for all operator combinations are reported in Table IV. Individual tooth-width measurements on the SureSmile models were consistently the most reproducible with the smallest mean squared errors between all 3 operator combinations. The measurements on the AnatoModels were consistently the third most reproducible, whereas those on the plaster models and the emodels interchanged from second to fourth most reproducible, depending on the operator combination.

The times required for completing the tooth-size measurements per set of models are reported in Table V. In general, it took the least time to complete the measurements on the emodels and the longest time to complete those on the AnatoModels. Differences among the 4 model types were statistically significant as follows. It took significantly longer to complete the measurements on the AnatoModels than on the emodels and the SureSmile models. It also took significantly longer to complete the measurements on the plaster models than on the emodels and the SureSmile models, and it took significantly longer to complete the measurements on the SureSmile models than on the emodels.

DISCUSSION

As technologies improve, orthodontists will continually have new tools to aid with diagnosis and treatment planning. It is the responsibility of the orthodontic community to weigh the advantages and disadvantages of these new tools to determine their clinical usefulness. This study was designed to provide a detailed look into the accuracy, reproducibility, and time efficiency of dental measurements on various types of digital models with multiple operators.

As with any new method, accuracy must be assessed by comparison with a gold standard—in this case, manual caliper measurements on plaster models.[4] Using this approach, we found that the tooth-width measurements taken on the digital models had both negative and

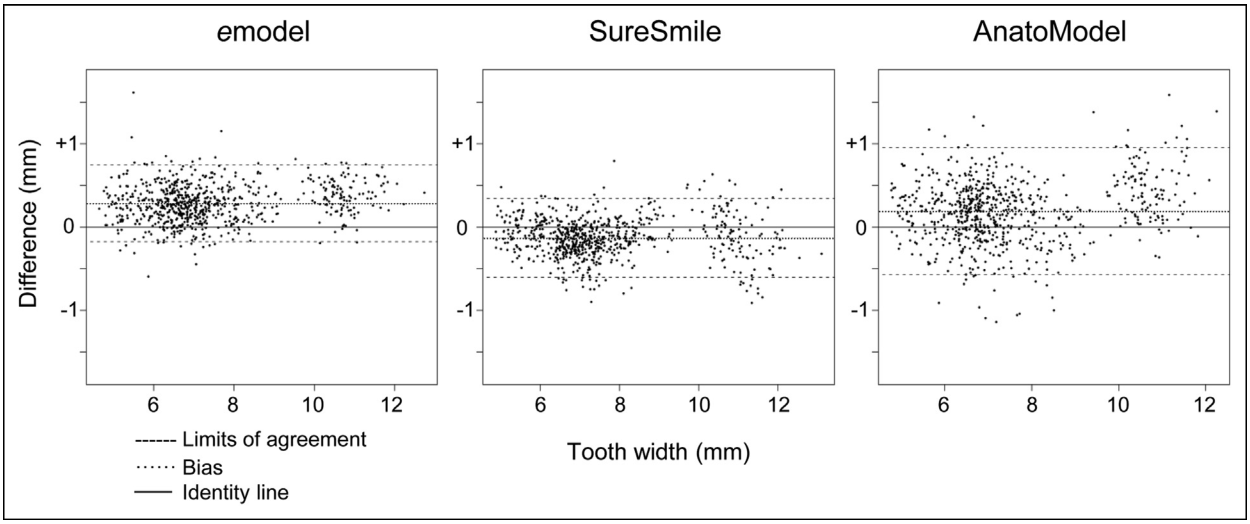

Fig 2. Bland-Altman plots for accuracy. Difference plots of emodels, SureSmile models, and AnatoModels compared with plaster models. The close proximity of the data points to the identity line in the SureSmile plot illustrates high relative accuracy, whereas the larger spread of the data points in the AnatoModels plot illustrates lower relative accuracy of the respective dental model.

Table IV. Reproducibility comparison of tooth-width measurements between raters

Operator comparison	*Model*	*Bias (mm)*	*Lower limit of agreement (mm)*	*Upper limit of agreement (mm)*	*Limit of agreement interval width (mm)*	*Mean squared error*
1 vs 2	Plaster model	0.413	−0.533	1.358	1.891	0.402
	emodel	0.996	0.001	1.991	1.990	1.239
	SureSmile model	0.143	−0.363	0.648	1.010	0.084
	AnatoModel	0.912	−0.293	2.116	2.408	1.200
1 vs 3	Plaster model	0.284	−0.448	1.016	1.464	0.227
	emodel	−0.162	−0.726	0.401	1.127	0.106
	SureSmile model	0.011	−0.316	0.338	0.654	0.032
	AnatoModel	0.035	−0.632	0.701	1.330	0.141
2 vs 3	Plaster model	−0.128	−0.814	0.557	1.370	0.138
	emodel	−1.158	−2.099	−0.218	1.881	1.563
	SureSmile model	−0.132	−0.668	0.404	1.072	0.095
	AnatoModel	−0.877	−1.984	0.231	2.214	1.092

positive biases: measurements on the SureSmile models had a small negative bias: ie, a tendency to underestimate tooth widths when compared with the plaster models. The measurements on emodels and AnatoModels had a moderate and a large positive bias, respectively. These findings agree with those of several other studies that have evaluated the accuracy of digital models created from plaster models.[4,16-19] In general, the differences were not considered clinically significant, and most authors have agreed that tooth-width measurements taken on digital models are accurate and reliable when compared with those on plaster models.[4,16,17,20-22]

Several reasons could be responsible for the slight inaccuracies. Since the same plaster model was used for the direct measurements and the digital replications, most of the reasons are probably attributable to an inherent distortion in the digital image or operator variation. One of the greatest sources of random error is the difficulty in identifying landmarks.[23] This is particularly a concern for digital models because a 3-dimensional structure is viewed as a 2-dimensional image, and identifying landmarks can become more difficult.[19,21] In addition, in some cases, the occlusal anatomy and interproximal areas were not defined well enough to be certain that the greatest mesiodistal diameter was being measured; this might have further increased the potential for measurement errors.

Although plaster models are currently considered the gold standard, this does not—or should not—imply that they are measured without errors.[13] Digital models could

Table V. Time comparisons among model types

	Plaster model	*emodel*	*SureSmile model*	*AnatoModel*
Time (s)	269 ± 44^{a,b}	168 ± 76^{a,c,d}	192 ± 55^{b,d,e}	272 ± 44^{c,e}

Results are mean values ± standard deviations.
Groups depicted by the same superscript letters are statistically significantly different ($P < 0.05$).

Table VI. Dental model pricing (June 2013)

Dental model	*Price (US dollars)**
Plaster model	2-5
emodel	30-40
SureSmile model	25-45
AnatoModel	50-75

*Exact amount depends on materials used for model fabrication and customer status. Prices are subject to change.

result in more valid measurements than plaster models because there is no physical barrier dictating placement of the measurement points.[17] It is most unlikely that calipers can reach the exact interproximal contact point of a tooth when that tooth is in contact with other teeth. Therefore, neither method can be regarded as providing unequivocally correct measurements.

New technologies, such as digital models, must work reproducibly in the hands of multiple operators. Accurate measurements have little value if they cannot be reproduced by other operators. In our study, reproducibility of the measurements was excellent in most cases and good in some; this agrees with a previous study on emodels.[17] SureSmile models yielded the most reproducible measurements for all 3 operator combinations. Interestingly, for the operator combination with some of the highest reproducibility values (1 vs 3; Table IV), the manual measurements on plaster models were the least reproducible. These findings suggest that there are instances in which digital technologies render more reproducible measurements and might be more advantageous to use.

The high reproducibility of measurements taken on the SureSmile models might be explained by the preset measuring points on these models, most of which the operators may have accepted without modifications. Therefore, and as an aside to the primary aims of this study, we performed a Bland-Altman analysis[12,13] to assess the differences between tooth-size measurements using operator-modified points and the preset points without modifications. When comparing the former to the latter, we found a bias of 0.0275 and limits of agreement of −0.2907 and 0.3458, which suggested that there are only minimal differences when an operator adjusts the preset measuring points.

In a busy orthodontic practice, the time available for model analysis is limited, and the time efficiency of dental measurements may play a major role in the selection of the dental model type. In this study, tooth-width measurements were, on average, performed the quickest in the following order: emodels (2 minutes, 48 seconds), SureSmile (3 minutes, 12 seconds), plaster models (4 minutes, 29 seconds), and AnatoModels (4 minutes, 32 seconds). The statistically significant differences among model types agree with those reported by Mullen et al,[18] who found measurements taken on emodels to be significantly faster than those on plaster models. For an orthodontic practitioner, however, clinically relevant time savings might be more important than statistically significant differences. It is reasonable to consider time savings of 20% to 25% compared with the gold standard clinically relevant. With the time required for the measurements on plaster casts in our study, this percentage amounts to about 1 minute. It can, therefore, be inferred that clinically relevant time savings can be achieved with emodels and SureSmile models. The difference between these models, with measurements on emodels on average 24 seconds faster than those on SureSmile models, does not, in contrast, appear to be clinically relevant.

The rather large standard deviations in the times required to complete the measurements suggest that individual results might vary. Some variations can be attributed to differences in measuring methods among the 3 operators. It has been shown that it takes more time when the operator rotates the model in any plane of space while taking tooth-width measurements than when the operator takes measurements only from the occlusal aspect.[24] Furthermore, the level of familiarity with a system, as with any method, can substantially influence the time needed to complete the measurements.

Another factor to be considered in the choice of a model type is cost-effectiveness. Not only do dental models need to be accurate, reproducible, and time-efficient, but they must be affordable. In general, plaster models are cheaper than digital models (Table VI) because the latter require the extra step of digitization. However, storage requirements can add significantly to the overall costs of plaster models.

When fabricating dental models, there is an inherent loss of information. When taking alginate impressions, fine details of tooth anatomy can be lost because of the inability of the impression material to flow into some areas. With digital models, there might be an additional loss of information inherent in the scanning process. Distances smaller than 0.015 mm cannot be accurately measured on emodels because of the resolution of the scan (M. Marshall, GeoDigm, personal communication,

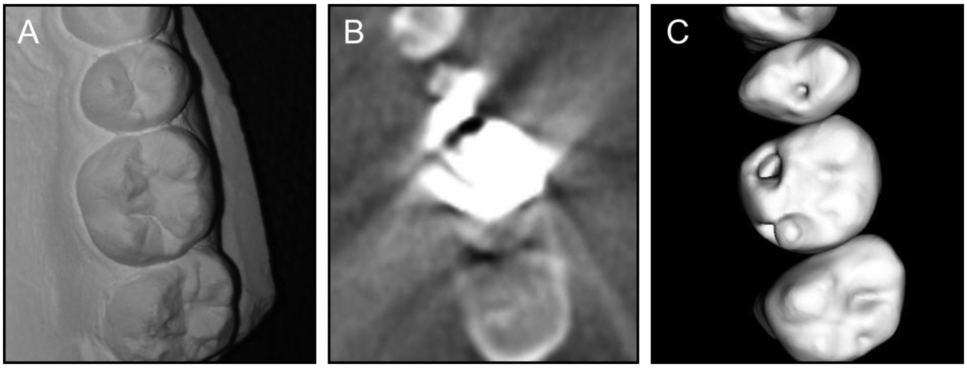

Fig 3. Artifacts in the CBCT volume can render normal tooth morphology impossible to reproduce: **A,** plaster model of a maxillary left first molar with a metallic restoration; **B,** streaking artifact in the CBCT volume; **C,** AnatoModel representation of the same molar.

March 5, 2013). Similarly, the SureSmile models and AnatoModels were fabricated from CBCT scans with voxel sizes of 0.2 and 0.3 mm^3, respectively; therefore, measurements smaller than 0.2 and 0.3 mm cannot be considered accurate on these models. Although the Anatomage software package allows measurements with a perceived accuracy of 0.01 mm, measurement accuracy is in fact limited by the resolution of the CBCT scan.

A comment must be made on the methodology used in this study. Although both the emodels and SureSmile models were fabricated from scans of the plaster models, the AnatoModels were fabricated directly from the CBCT scans of the patients because these models are marketed as "impressionless study models purely from CBCT." Although the idea of gathering all diagnostic records from a single CBCT scan is most intriguing to the orthodontic specialty, digital models fabricated directly from CBCT volumes might be affected by scanning artifacts. These artifacts can degrade the image quality and might originate from various sources. Physics-based artifacts result from the physical processes involved in the acquisition of the CBCT data, whereas patient-based artifacts are caused by such factors as patient movement or metal objects in the patient. Metallic dental restorations in the scan field can lead to streaking artifacts, which occur because the density of the metal is beyond the normal range that can be handled by the computer, resulting in incomplete attenuation profiles.[25] When dental anatomy cannot be accurately reproduced, these streaking artifacts might affect tooth-width measurements on CBCT-based models (Fig 3). Additional artifacts due to beam hardening, partial volume, and aliasing are likely to compound the problem.

After analyzing accuracy, reproducibility, and time efficiency of tooth-width measurements, we identified a model type that consistently rendered more accurate and reproducible measurements than the others: when compared with the plaster models, the SureSmile models were the most accurate, the most reproducible, and the second fastest for tooth-width measurements. Although plaster models were used as the reference to which the digital models were compared, they allowed neither the most reproducible nor the quickest measurements. Therefore, as orthodontic technology continues to rapidly progress, and with enhancement of digital point recognition, we might soon see digital models replacing plaster models as the gold standard because of their high accuracy, reproducibility, and time efficiency.

CONCLUSIONS

Dental measurements taken on digital models can be as accurate as, and might be more reproducible and significantly faster than, those taken manually on traditional plaster models. Of the model types studied, the SureSmile models provided the best combination of accuracy, reproducibility, and time efficiency of measurement.

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