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Comparison of reconstructed rapid prototyping models produced by 3-dimensional printing and conventional stone models with different degrees of crowding

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Introduction: Rapid prototyping models can be reconstructed from stereolithographic digital study model data to produce hard-copy casts. In this study, we aimed to compare agreement and accuracy of measurements made with rapid prototyping and stone models for different degrees of crowding. **Methods:** The Z Printer 450 (3D Systems, Rock Hill, SC) reprinted 10 sets of models for each category of crowding (mild, moderate, and severe) scanned using a structured-light scanner (Maestro 3D, AGE Solutions, Pisa, Italy). Stone and RP models were measured using digital calipers for tooth sizes in the mesiodistal, buccolingual, and crown height planes and for arch dimension measurements. Bland-Altman and paired *t* test analyses were used to assess agreement and accuracy. Clinical significance was set at ±0.50 mm. **Results:** Bland-Altman analysis showed the mean bias of measurements between the models to be within ±0.15 mm (SD, ±0.40 mm), but the 95% limits of agreement exceeded the cutoff point of ±0.50 mm (lower range, −0.81 to −0.41 mm; upper range, 0.34 to 0.76 mm). Paired *t* tests showed statistically significant differences for all planes in all categories of crowding except for crown height in the moderate crowding group and arch dimensions in the mild and moderate crowding groups. **Conclusions:** The rapid prototyping models were not clinically comparable with conventional stone models regardless of the degree of crowding. (Am J Orthod Dentofacial Orthop 2017;151:209-18)

Three-dimensional (3D) digital anatomic models are becoming more acceptable in practice to replace conventional stone study models.[1] The special advantage of these digital models is their ease of storage, data retrieval, and transferability to overcome the shortcomings of physical models, which not only require a large storage area and risk damage leading to information loss, but also are inconvenient to share with other clinicians. Institutions with large collections of historic patient study models that are kept for medicolegal reasons and research purposes could address the issue of storage space by scanning and storing these models in digital format. However, some may hesitate to dispose of these stone models after the records are kept in digital format because there may be occasions, such as in medicolegal circumstances, when tangible records are required. An emerging technology called rapid prototyping (RP) to produce graspable 3D objects directly from digital models may be able to address this need for physical models. This technology can be categorized as an additive manufacturing process, which first slices the digital model into layers of a certain thickness and then prepares the physical model by building layer upon layer.[2] However convenient RP may be, we must investigate this tool to ascertain whether it could be a clinically acceptable alternative to stone study models.

In medicine and dentistry, RP technologies have gained interest for such applications as manufacture of

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anatomic models as aids for visualization, diagnosis, discussion, and surgical planning, especially for neurologic and oral and maxillofacial surgery.[3] Examples of RP techniques used include 3D printing, stereolithography, selective laser sintering, and fused deposition manufacturing. The fabrication versatility of 3D printing is evident in its ability to fabricate the full spectrum of powder materials (ceramics, metals, and polymers) and its ability to control pore characteristics (size, morphology, and volume fraction) with high repeatability and reproducibility. This method allows the manipulation of the chemical, physical, and mechanical properties of the manufactured product. These characteristics are particularly desirable for biocompatible applications such as implantable materials and tissue-engineered scaffolds for medical and dental devices.[4] Describing and explaining plans for complex craniomaxillofacial procedures in orthognathic surgery, which can be conceptually difficult, may become less challenging with 3D medical modeling. This RP method assists in the preparation of operative procedures by producing an exact copy of the patient's skull and facial structures based on radiographic data, which allow surgeons to visually simulate osteotomies before surgery.[5] More recent applications include the use of rapid prototype wafers for surgical models. The rapid prototype wafers were based on virtual wafers derived from laser scans of dental models using computer-aided design and computer-aided manufacture software.[6]

Few studies have compared conventional and reconstructed models. Germani and Raffaeli[7] compared 4 types of RP study models, 2 of which were manufactured using different materials. All replicas had varying degrees of small dimensional errors that were influenced by the size of the detail to be reproduced. However, the effect of the reduced detail in dental morphology on the clinical acceptability was not within the scope of the study. Due to financial constraints, Keating et al[8] compared a reconstructed model generated by the SLA-250/40 stereolithographic machine (3D Systems, Rock Hill, SC) with a build-layer thickness of 0.15 mm with its original conventional stone model. They found that the statistically significant differences were mainly due to errors in the vertical thickness of the z-plane measured based on crown heights (mean difference, 0.42 mm; SD, 0.23 mm) attributed to the RP method, which builds the model layer by layer, and the layering method and model translucency, which resulted in some loss in surface detail and made landmark identification difficult. Kasparova et al[9] found no significant differences between conventional and RP models constructed using the RepRap 3D printer with a build thickness of 0.35 mm. The differences between the plaster and RP models were not statistically significant. However, they limited their measurements to 1 linear measurement for each x-, y-, and z-axis and a mixed x-y axis. Based on standard deviations that were less than 0.50 mm, they concluded that RP models had acceptable clinical accuracy compared with conventional models.

None of these authors investigated the influence of crowding on the accuracy of the reconstructed models. In crowded areas, teeth can overlap, and it may be more difficult to reproduce with good accuracy the undercut areas that are blocked from the sensor's view during scanning. Fleming et al[1] reviewed studies that compared conventional and digital models. They found varying reported results but minimal differences and seemed to advocate the differences as clinically acceptable. However, data distortion during data conversion and manipulation to convert the digital surface information to the stereolithography file format[10,11] and the subsequent model shrinkage during building and postcuring from the RP technique[12] may further influence the accuracy of the reconstructed models.

The aim of this study was to compare orthodontic stone models with the 3D printed RP models across degrees of crowding. To date, no studies have been published evaluating the clinical acceptability of the reconstructed models using the Z Printer 450 (3D Systems), which has a build-layer thickness of 0.089 to 0.102 mm, as duplicates to conventional models for different degrees of crowding. This study will be of particular interest in determining institutional record-keeping policy whether to dispose of conventional stone models that have been digitally scanned before the limit of the national legally required time for retention of clinical records.

MATERIAL AND METHODS

Ethical approval for this study was obtained from the medical ethics committee, Faculty of Dentistry, University of Malaya (DF CD1303/0016[P]), Kuala Lumpur, Malaysia.

Sample size estimation was based on a previous study by Keating et al[8] and calculated using PS Software (Power and Sample Size Calculations version 3.0.17; William D Dupont and W Dale Plummer Jr, Department of Biostatistics, Vanderbilt University, Nashville, Tenn.). For the RP model, a minimum of 10 models per category of crowding was required for a 90% chance to detect a related sample mean with a difference of 0.26 mm and a standard deviation of 0.22 mm at the 5% level of significance (power, 0.90; α, 0.05; δ, 0.26; and σ, 0.22).

Crowding was estimated based on the total mesiodistal width against the available space in the arch.

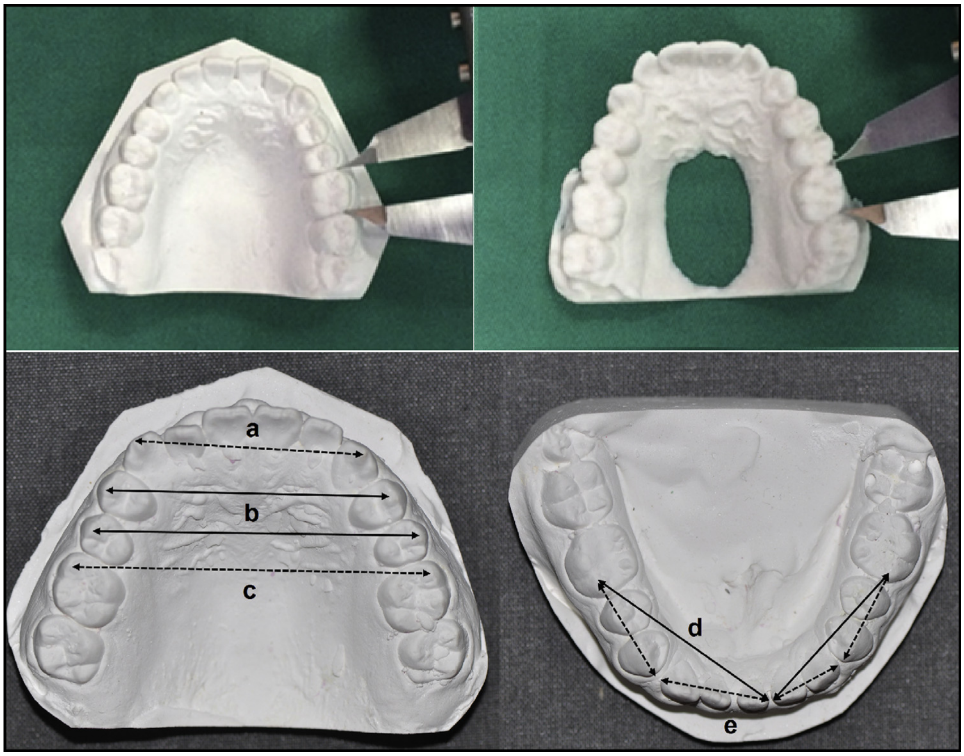

Fig 1. Measurements using the digital caliper on a conventional stone model (*top left*) and a reconstructed model (*top right*). Landmark points for the arch dimensions: *a*, intercanine width; *b*, interfirst and intersecond premolar widths; *c*, intermolar width (*bottom left*); and *d*, arch length; and *e*, arch perimeter segments (*bottom right*).

The degree of crowding was classified as mild (1-4 mm), moderate (5-8 mm), or severe (>9 mm).[13] New models were used to exclude any confounding caused by variability of the materials used to cast the plaster models. Impressions were taken from recruited patients on the orthodontic waiting list. The inclusion criteria were mild, moderate, or severe crowding in any malocclusion, and fully erupted complete permanent dentition from first molar to contralateral first molar. The exclusion criteria were previous or ongoing orthodontic treatment and significant dental anomalies, eg, supernumerary teeth or an abnormal tooth shape that could obscure landmark identification. The study models included were those with good surface details; those with surface marks, voids, and fractures were excluded.

Study models were cast in white stone (Elite Ortho; Zhermack, Badia Polesine, Italy). The stone models were scanned using a structured light scanner (Maestro 3D; AGE Solutions, Pisa, Italy) via EasyDentalScan software (AGE Solutions) and exported as binary stereolithographic files. The base area of each digital model was trimmed using biomodeling software (BioModroid; CBMTI, Kuala Lumpur, Malaysia). The size of the models was reduced to preserve only the dentition and the immediate alveolar bases to minimize printing costs, which were proportional to the dimensions of the model. The models were produced using the RP machine (Z Printer 450; 3D Systems). The printing material comprised high performance composite (Zp151; 3D Systems). A clear binder (Zb63; 3D Systems) was used during the curing process. Modeling infiltrant (Z-bond 101; 3D Systems) was used during postprocessing to strengthen the printed model.

For the stone and RP models, measurements of parameters were taken with a hand-held digital caliper (Fowler High Precision Tools & Measuring Instruments, Newton, Mass) to the nearest 0.01 mm (Fig 1).

To assess whether the quality of the RP models would be clinically acceptable for linear measurements, measurements were made of clinically relevant parameters: tooth sizes and arch dimensions. Tooth sizes were further defined as follows.

1. Mesiodistal widths. The greatest mesiodistal diameter from the anatomic mesial contact point to the

anatomic distal contact point of each tooth parallel to the occlusal plane.

2. Buccolingual or palatal widths. Distance between the maximum concavities of the buccal and lingual surfaces.
3. Clinical crown height. Distance between the cusp tip to the cervical level.

Arch dimensions (Fig 1) comprised the following.

1. Intercanine width. Distance between the occlusal tips of the canines.
2. Interpremolar width. Distance between the buccal cusp tips of the contralateral first and second premolars.
3. Intermolar width. Distance between the mesiobuccal cusp tips of the contralateral first molars.
4. Arch length. Diagonal distance between the mesiobuccal cusp tips of the first molars and the mesiodistal contact areas of the central incisors.
5. Arch perimeter segments. Sum of the bilateral arch segments. The first segment is the distance between the distal measurement point of the first molar and the mesial contact point of the first premolar; the second segment is the distance from the distal contact point of the canine to the mesial contact point of the central incisor.

To assess operator reliability in measurements using the digital caliper, 3 pairs of study models (10% of the sample), each comprising a pair from each category, were randomly selected using online Research Randomizer (www.randomizer.org) software. For intraexaminer reliability, each study model was measured by the same examiner (Y.Y.) on 2 occasions with an interval of at least 2 weeks. The first measurements were compared with those obtained by a second examiner (W.N.W.H.) for assessment of interoperator reliability.

Statistical analysis

Data were analyzed with SPSS software (version 12.0.1; SPSS, Chicago, Ill) and MedCalc software (MedCalc, Ostend, Belgium).

The intraexaminer and interexaminer reliability values for individual parameters were assessed using the intraclass correlation coefficient (ICC): an ICC less than 0.40 is considered poor, between 0.40 and 0.75 is fair to good, and more than 0.75 is excellent.[14] To reduce statistical errors due to multiple analyses, the parameters were compared in terms of the differences in tooth size in the 3 planes (mesiodistal, buccolingual, and crown height) and arch dimensions rather than by individual parameters. Histograms and quantile-quantile plots indicated that the differences between measurements made on the stone and RP models were normally distributed for the different degrees of crowding (mild, moderate, and severe). Bland-Altman analysis was done to assess agreement, and paired *t* tests were used for accuracy of the measurements between the 2 types of study models based on the degree of crowding. Clinical significance was set at 0.50 mm.[9,15]

RESULTS

The sample comprised 10 sets of study models for each category of crowding. Figure 2, *A*, shows that generally the fine details of the models (fissures and cervical margins) were incrementally reduced as the models transformed from stone to digital and then to RP models. Stone models generally have smooth surfaces and show well-defined boundaries of the interproximal contact points and cervical margins, which demarcate the anatomy of each tooth from the adjacent teeth and from the gingival margins. Minor artifacts such as air bubbles and slightly excessive stone materials were observed but were considered negligible because they were small and away from the landmarks used for measurements. On the other hand, the surfaces of the RP models were coarse. The models were well intact even though the surfaces appeared flaky. The cervical margins, fissures, fossae, and cuspal tips of the RP models were also less defined than the original stone models (Fig 2, *B*). The minor artifacts on the stone models were generally not replicated like the original models or had less obvious margins; this made the distinction between normal anatomic boundaries and artifacts less recognizable than on the stone models. Interproximal contact points were also less demarcated, with additional artifacts observed especially in areas close to the undercuts between overlapped teeth. At the sites of crowding, the clinical impression was that as the degree of crowding increased, the contact areas between the crowded teeth were also less defined and more likely to have a slight surplus of artifacts.

For measurements using the digital caliper, the intraoperator ICC values had excellent agreement (>0.75) and ranged from 0.817 to 0.999. The interoperator ICC values also had excellent agreement, ranging from 0.818 to 0.999.

Figure 3 shows the Bland-Altman plots of the differences between the measurements made on the stone and RP models (x-axis) against the average values of the measurements made on the 2 models (y-axis). The plots were randomly distributed along the mean bias line for all planes and degrees of crowding, indicating that the differences did not depend on the magnitude of the measurements. Systematic bias was observed where the mean bias line tended to be slightly lower

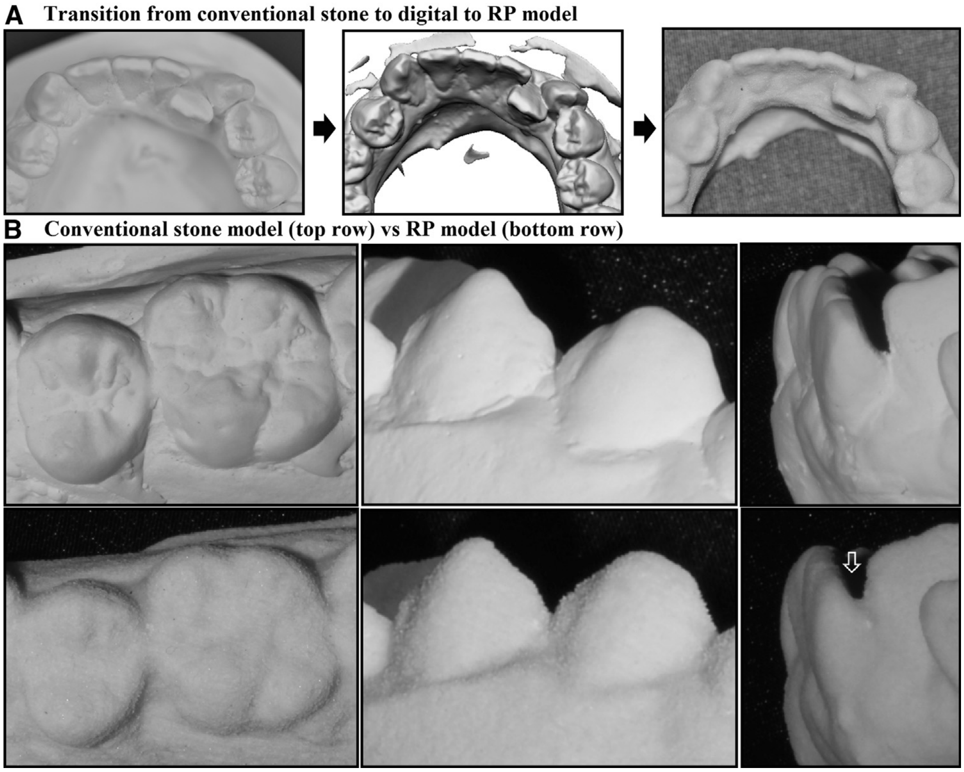

Fig 2. **A,** Close-up views comparing the conventional stone (*left*) and the RP (*right*) models; the transition phase of the digitized model (*middle*) showed some preservation of surface details, but most of the detailed definitions appeared to be lost after the model was reconstructed. **B,** Close-up photographs of the original conventional study models (*top row*) and RP models (*bottom row*); the cuspal tips, fissures, and fossae (*left column*) and cervical margins (*middle column*) of the RP models were less defined; artifacts were also noted (*arrow*) in areas between overlapped teeth (*right column*) on some RP models.

(RP was larger) in the mesiodistal plane but slightly higher (RP was smaller) in the buccolingual plane for all categories of crowding. The systematic bias values for the crown height and arch dimension planes were close to the 0 line.

The Table, for the Bland-Altman analysis, shows that the mean bias between the stone and RP models for the different degrees of crowding in all planes was small and was within ±0.15 mm, with standard deviations that were within ±0.40 mm. However, for most measurements, the 95% limits of agreement were beyond the cutoff points of acceptable clinical difference (greater than ±0.50 mm).

The Table, for the paired *t* test, shows that the models were significantly different ($P < 0.05$) for all degrees of crowding: measurements made on the RP models were slightly larger in the mesiodistal plane (mean range, −0.15 to −0.11 mm; SD, 0.28 to 0.31 mm) but smaller in the buccolingual plane (mean range, 0.10 to 0.15 mm; SD, 0.28 to 0.38 mm). In the crown height plane, the differences were only marginally significantly different, by −0.05 mm (SD, 0.31 mm; 95% CI, −0.09 to −0.01 mm) for the mild crowding group and by −0.06 mm (SD, 0.36 mm; 95 CI, −0.10 to −0.01 mm) for the severe crowding group. In the arch dimensions plane, statistically significant differences were detected, with RP models showing larger measurements in the severe crowding group by −0.06 mm (SD, 0.38 mm; 95% CI, −0.11 to −0.00 mm).

DISCUSSION

In this study, we assessed the potential use of the RP study models constructed using the Z Printer 450 as an alternative for the original plaster models. The RP models were constructed with a build-layer thickness that was thinner than that used in previous studies.[8,9] RP models offer the advantage of reproducing hard-copy casts from digital data storage on demand. However, technical errors may cause loss of information of the digital data.[9] Factors that could affect the quality of the RP models include the scanning and printing processes. The former

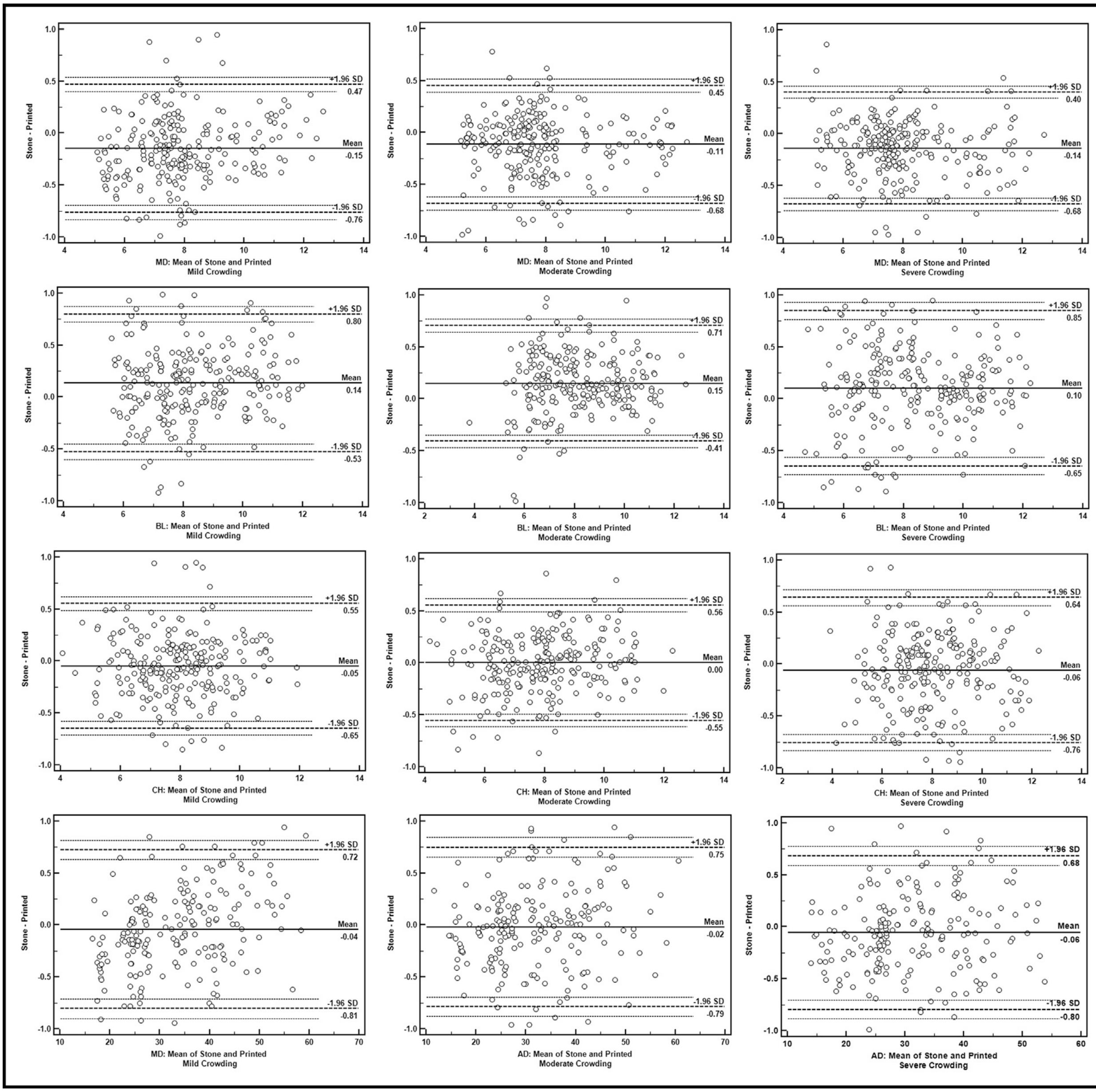

Fig 3. Bland-Altman plots of measurements made between stone and RP models for mild (*left column*), moderate (*middle column*), and severe (*right column*) crowding. Rows top to bottom represent measurements made in the mesiodistal, buccolingual, and crown height planes of the teeth, and the arch dimensions plane. For each plot, the x-axis represents differences between stone and RP models, and the y-axis represents the average between the measurements made on the stone and RP models. The *thick middle line* represents the mean bias. The *upper and lower hashed lines* represent the upper and lower 95% limits of agreements, respectively. The *thin lines* represent the upper and lower 95% confidence intervals of the limits of agreement. All measurements are in millimeters.

may be influenced by the accuracy of the scanner. In this study, the Maestro 3D structured light scanner was used to obtain the digital models. General observation demonstrated that scanning conventional stone models and converting them into digital format was associated with some loss of fine surface details; this could be a result of loss of information caused by data distortion during conversion to the stereolithography file format.[10,11] The clinical implications of this reduction in detail was not easy to quantify. A previous study demonstrated agreement

Table. Bland-Altman and paired t test analyses comparing the RP and stone models

		Bland-Altman (stone minus RP) in mm								Paired t test (stone minus RP) in mm				
				95% limits of agreement								95% CI		
Plane (n)	Crowding	Mean bias	SD	Lower limit	95% CI of lower limit		Upper limit	95% CI of upper limit		Mean	SD	Lower	Upper	P value
MD (240)	Mild	−0.15	0.31	−0.73	−0.86	−0.69	0.47	0.40	0.54	−0.15	0.31	−0.19	−0.11	0.000*
	Moderate	−0.11	0.29	−0.68	−0.74	−0.62	0.45	0.39	0.52	−0.11	0.29	−0.15	−0.08	0.000*
	Severe	−0.14	0.28	−0.68	−0.74	−0.62	0.40	0.34	0.46	−0.14	0.28	−0.17	−0.10	0.000*
BL (240)	Mild	0.14	0.34	−0.53	−0.60	−0.45	0.80	0.72	−0.87	0.14	0.34	0.09	0.18	0.000*
	Moderate	0.15	0.28	−0.41	−0.47	−0.35	0.71	0.64	0.77	0.15	0.28	0.11	0.19	0.000*
	Severe	0.10	0.38	−0.65	−0.73	−0.53	0.85	0.76	0.93	0.10	0.38	0.05	0.15	0.000*
CH (240)	Mild	−0.05	0.31	−0.65	−0.71	−0.58	0.55	0.49	0.62	−0.05	0.31	−0.09	−0.01	0.000*
	Moderate	0.00	0.28	−0.55	−0.62	−0.49	0.56	0.49	0.62	0.00	0.28	−0.04	0.04	0.967
	Severe	−0.06	0.36	−0.76	−0.83	−0.68	0.64	0.56	0.72	−0.06	0.36	−0.10	−0.01	0.012*
AD (200)	Mild	−0.04	0.39	−0.81	−0.90	−0.71	0.72	0.63	0.81	−0.04	0.39	−0.10	0.01	0.126
	Moderate	−0.02	0.39	−0.79	−0.88	−0.69	0.75	0.66	0.84	−0.02	0.39	−0.07	0.04	0.499
	Severe	−0.06	0.38	−0.80	−0.89	−0.71	0.68	0.59	0.77	−0.06	0.38	−0.11	−0.00	0.036*

The numbers in the first column (n) are the total numbers of the measured planes.
MD, Mesiodistal; *BL*, buccolingual; *CH*, crown height; *AD*, arch dimension measurements.
*$P < 0.05$.

within acceptable clinical significance for measurements made on similar planes between conventional models with less than 4 mm of contact point displacements and the digital models scanned using this scanner.[16] The reduced detail was found not to affect the clinical measurements for tooth sizes and arch dimensions. Thus, the scanner was considered a satisfactory machine to produce digital models with clinically acceptable quality. However, that study was limited to relatively well-aligned models. The degree of crowding may confound the accuracy of the digital models, since undercuts may be missed during the scanning process. Other studies that compared linear measurements on digital models with those on conventional models in terms of crowding found variable results.[17-21] In our study, qualitative observation showed that the reduced detail in the undercut areas also resulted in loss in anatomic details of the reconstructed model. This may have influenced the results because it increased the difficulty in identifying the landmarks for measurements.

In terms of the printing process, the accuracy of the reconstructed models may be affected by the accuracy of the machine, the materials used, and the subsequent model shrinkage during building and postcuring from the RP technique.[12] The technology behind the RP technique is beyond the scope of this article but will be briefly described. Reconstructed models are made similarly to 2-dimensional inkjet printing but in layers. A piston that dispenses the reconstructed model powder from a supply chamber moves upward incrementally before a roller distributes the powder to compress it at the top of the production chamber. Liquid adhesive that binds the powder together is then deposited onto the powder layer before the next powder layer is deposited. This process continues until the prototype is constructed based on the digital information supplied. The prototype then undergoes heat treatment to set the material.[22] Three-dimensional printing is unique among the various RP systems in its inherent flexibility. When 3D printing was compared with other RP systems, its resolution was competitive with most RP processes.[7] Minimum feature size is on the order of 150 to 200 μm with some variations, depending on the powder and the binder selection.[4] One major benefit of 3D printing is the variety of choices available for the material.[4] However, for this study, the selection of material was based on the manufacturer's recommendation.

In this study, the reconstructed models were built in thinner layers of 0.089 to 0.102 mm with high-performance composite resin. Zp151 has a strong green strength to produce robust, improved parts in high definition. Green strength is the handling strength of parts immediately after they are removed from RP system, before any postprocessing.[23] The constructed part will be in bright white and can be improved with postprocessing using Z-bond 101. Color or whiteness helped to give an opaque or nontranslucent appearance to the reconstructed models that facilitated landmark identification, since translucent models may make landmark identification difficult.[8] During printing, zb63 was spread in 2-dimensional directions on powder (zp151) to create bonded layers based on information from ZCorp software of the part to be printed. Z-Bond 101 was applied to the reconstructed model for postprocessing. The advantages of Z-bond 101 are that it is fast and easy to apply, it is 3 times stronger than wax, and it helps to produce vibrant and light-fast color models.

A few studies have been done to compare reconstructed and conventional stone models. As already noted, Keating et al[8] printed only 1 model, built in 0.15-mm layers of clear resin. They made the measurements in the x-, y-, and z-planes and found an overall mean difference of 0.26 mm (SD, 0.22 mm), which was significantly higher than that in our study. However, their mean difference of 0.42 mm (SD, 0.23 mm) in the z-plane (vertical dimension) was statistically significant (P <0.00). They also found that the z-plane measurements of the reconstructed model were significantly smaller than those for the plaster and digital models. Kasparova et al[9] compared the accuracy of 10 plaster models and replicated models produced by the RepRap 3D printer, where thin plastic lines were laid down to build the plastic object. Their measurements were limited to 4 measurements of interest: intercanine width (represented on the x-axis), distance between the canine tip and the permanent first molar mesiopalatal cusp (represented on the y-axis), crown height of the canine (represented on the z-axis), and mesial edge of the central incisor to the tip of the canine (represented on mixed axes). They found no statistically significant differences between the distance measurements on the plaster models and those on the printed models. Accuracy also was estimated based on the standard deviations of differences between these 2 models. With standard deviations of the differences between the models of less than 0.50 mm, they suggested that the RepRap 3D printed models with the build-layer thickness of 0.35 mm could replace conventional models. The limitation of the study by Kasparova et al was that accuracy was evaluated by comparing distances in the x-, y-, and z-planes. However, it is not known whether measurements of teeth and arch dimensions on those models are clinically comparable with the original casts.

We evaluated the effect of crowding on the agreement and accuracy for linear measurements of RP study models. For all planes and degrees of crowding, the mean bias values were small (within ±0.15 mm and SD, <0.40 mm), but the 95% limits of agreement were beyond the acceptable clinical significance of 0.5 mm. We found statistically significant differences in the measurements made in the mesiodistal and buccolingual planes between the stone and RP models. Since the teeth are arranged in a U-shaped arch, the x- and y-planes are interchangeable for the mesiodistal and buccolingual planes. In theory, the RP method in either plane should be similar, since the model is made in increments layer by layer from the base of the model to the tip of the cusps. Even though the differences were small, the trend indicated that the RP models were larger in the mesiodistal planes but smaller in the buccolingual planes. The differences in the crown height and arch dimension planes were much smaller, and some were also not significantly different. Several reasons may have contributed to the differences: errors in the transition from scanning to printing, crowding, and less defined landmarks in the RP models. Mesiodistal, buccolingual, and arch dimension planes represent measurements in the mixed x-y planes, whereas the crown height represents measurements in the z-plane. From scanning to printing, the 3 planes may suffer from shrinkage or expansion error, which may explain the significant differences between the 2 models, especially in the mesiodistal and buccolingual planes. However, the differences in the arch dimension plane were much smaller than those in the mesiodistal and buccolingual planes, and some were also not significantly different. These differences were conflicting and failed to explain whether there was consistent shrinkage or expansion in the x-y planes after printing. The other possible confounder to the differences between the models may have been the difficulty of measuring in the crowded areas. Crowding made measurements and identification of landmarks more challenging because the tip of the digital caliper could not reach the desired landmarks as accurately as desired (Fig 4). The less-defined surface detail on the RP models also made locating the landmarks for measurements challenging (Figs 2, *B*, and 4). It was observed that the digitized models had reduced surface details, which in turn caused loss of surface details in the RP models. Contact points between adjacent teeth were slightly thicker and less defined; this may have contributed to the slightly larger mesiodistal measurements in the RP models, since their landmarks are usually located where teeth are in contact with adjacent teeth, and most teeth are in contact with each other except when they are displaced because of crowding.

In the z-plane (crown height), significant differences (P <0.05) were detected in the mild (mean, −0.05 mm; 95% CI, −0.09 to −0.01 mm) and severe (mean, −0.06 mm; 95% CI, −0.10 to −0.01 mm) crowding groups, but the differences were small. The differences were much smaller than the difference of 0.42 mm in the z-plane found by Keating et al.[8] It is possible that the better build thickness of the Z Printer 450 was able to construct the layers of the models with a much smaller difference and greater accuracy than the SLA-250/40 machine. The wider standard deviations in this study (range, 0.28-0.36 mm) than those in their study (0.23 mm) may be accounted for by a larger sample

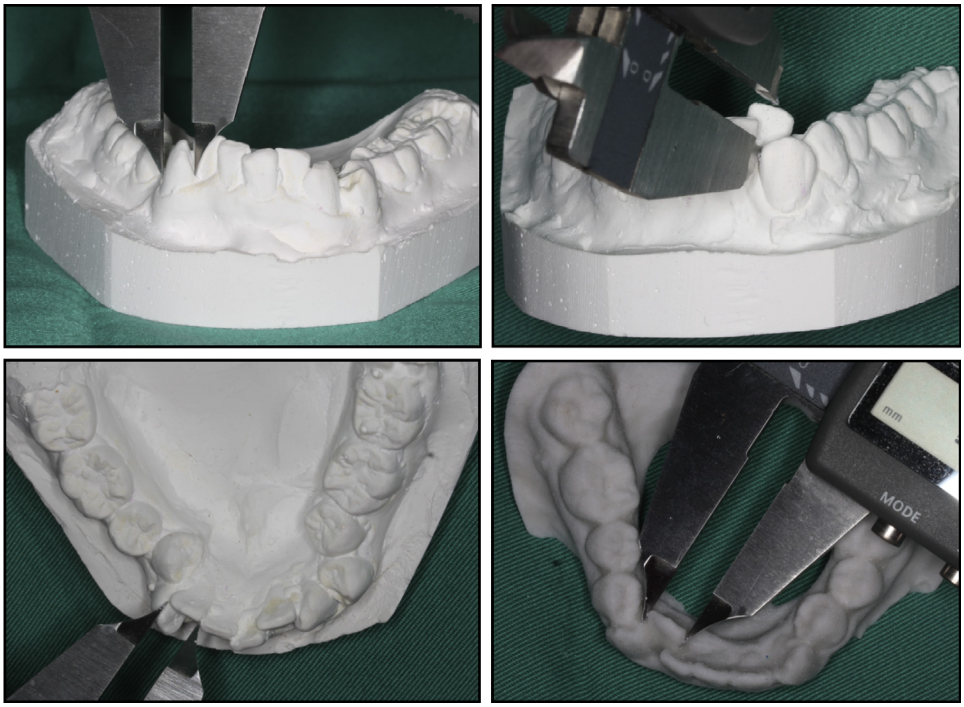

Fig 4. Problems encountered in measuring the models that accounted for errors such as difficulty in measuring buccolingual widths (*top left*), crown height (*top right*), and mesiodistal widths (*bottom left*) on the study models. The less-defined contact points in the severely crowded areas also made measurements more difficult on the reconstructed models (*bottom right*).

size in this study. Similar to the issues faced in the other planes, reduced surface details of the crown height landmarks—the cuspal tips and cervical margins—made them harder to locate and would have contributed to the significant differences in measurements between the RP and the conventional models.

Reconstructed models are gaining popularity to aid visualization, discussion, and surgical planning of complex craniofacial cases.[3] These orthognathic surgical cases may involve orthodontic treatment. The RP models can be used during multidisciplinary discussions. Based on this study, if discrepancies within 1.0 mm are considered acceptable for craniofacial surgeries, then the 3D printing models can be considered clinically acceptable. However, in orthodontic treatment planning, a 0.5-mm difference is considered clinically significant because it would influence predictions for space requirements and tooth-size discrepancies. Therefore, if such cases involve measuring tooth sizes where discrepancies of more than 0.5 mm are considered clinically unacceptable, then the 3D printing models could not be relied on with acceptable clinical confidence. If these RP models were used during discussions, it is recommended to refer to the original casts or digital models if the teeth or arch dimensions need to be measured.

Reconstructed models have been used in orthodontics for manufacturing appliances such as clear aligners, customized lingual brackets, and retainers. The materials used vary, and most large manufacturing companies such as Invisalign and Incognito do not disclose the materials used for their reconstructed models. Since this study was limited to assessing the agreement and accuracy of measurements between stone and 3D printing models, it should not be extrapolated that appliances made on these models may not fit intraorally. Germani and Raffaeli[7] found that all types of reconstructed dental models in their tests, which included the 3D printing model, had some dimensional and morphologic errors. Generally, accuracy of working models for orthodontic appliances is less demanding than construction of restorative or prosthodontic appliances such as crowns, bridges, and posts. In practice, orthodontic appliances are made on working models that are usually cast from alginate impression materials. Restorative or prosthodontic appliances are often made on working models that have been cast from silicone impression materials, which have better stability and accuracy compared with alginates that have more discrepancies with increased storage time.[24] The reduced morphologic detail of the 3D printing models especially in the areas used in landmark identification for measuring teeth or arch dimensions most likely influenced the outcome of this study. Such loss in the details of the cervical margins, fissures, fossae, and cuspal tips may not necessarily be critical for the construction of orthodontic appliances, since the shape and size of the teeth and arch forms of the 3D printing models were similar to the original casts. Further research is recommended to assess the clinical applicability of the reconstructed models for appliance construction.

CONCLUSIONS

Measurements made on RP models reconstructed using the Z Printer 450 reproduced from digital models by the Maestro 3D structured light scanner were not clinically comparable with conventional stone models regardless of the degree of crowding. These RP models may not be an acceptable replacement for conventional stone models.

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