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Effect of print layer height on the assessment of 3D-printed models

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Introduction: Many variables can affect the accuracy of 3D-printed orthodontic models, and the effects of different printing parameters on the clinical utility of the printed models are just beginning to be understood. The objective of this study was to investigate the effect of print layer height on the assessment of 3D-printed orthodontic models with the use of the American Board of Orthodontics Cast-Radiograph Evaluation grading system. **Methods:** Twelve cases were scanned using a desktop model scanner and 3D-printed using a stereolithography-based printer at three different layer heights (25, 50, and 100-μm; n = 12 per group). All models were scored by eleven graders using the Cast-Radiograph Evaluation grading system. All models were scored a second time, at least two weeks later. **Results:** No statistically significant effects of print layer height were found on the scoring of the models for any of the grading metrics or total score. 3D-printed models of each layer height were highly positively correlated with stone models for the total score, with the strongest correlation found with models printed at 100-μm. **Conclusions:** 100-μm layer height 3D-printed models are potentially clinically acceptable for the purposes of evaluation of treatment outcomes, diagnosis and treatment planning, and residency training. (Am J Orthod Dentofacial Orthop 2019;156:283-9)

Three-dimensional (3D) printing technologies enable the production of physical objects from digital files, and orthodontists are embracing these emerging technologies for a range of clinical applications. For example, 3D printers are being used to fabricate models of teeth from cone-beam computed tomographic scans for tooth transplantation procedures,[1] the fabrication of orthodontic auxillaries,[2] and the production of orthodontic brackets.[3] Invisalign has been printing 3D models for years to support fabrication of clear aligners, and now many commercial and in-office laboratories are following suit. In each case, the prudent practitioner should consider the variables associated with 3D printing in the context of the envisioned application. These variables can influence print accuracy and as a result affect the potential clinical utility of printed parts.

Recent studies have investigated the effect of some of these variables on the accuracy of models produced by 3D printing. Multiple studies have evaluated the accuracy of 3D-printed models compared with stone models as the criterion standard, finding that when comparing linear measurements, 3D-printed models are acceptable within clinical tolerances,[4,5] which have been suggested previously to fall in a range of 0.2-0.5 mm.[6-8] Multiple studies have investigated the effect of print layer height and different printer types on the accuracy of 3D-printed models, concluding that both variables statistically significantly affect the accuracy of the printed models, but the impact should be considered with respect to the clinical tolerances associated with the envisioned application.[9,10] Other studies have evaluated the effect of print orientation on model accuracy and surface smoothness,[11] base design on model accuracy, especially in reference to linear measurements in the transverse dimension,[12] and the effect of crowding on the accuracy of linear measurements made on 3D-printed models.[13] These and other studies collectively report the effects of a range of variables on the accuracy of 3D-printed models, but most studies

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All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.
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Submitted, June 2018; revised and accepted, February 2019.
0889-5406/$36.00

https://doi.org/10.1016/j.ajodo.2019.02.013

Table I. Calculated mean ± standard deviation print times, resin volumes, and numbers of layers associated with printing the model sets (one set at a time) at each layer height investigated

Layer height (μm)	Print time	Resin volume (mL)	Number of layers
25	19 h 13 min ± 1 h 14 min[a]	142.5 ± 12.5[d]	1358.8 ± 33.3[e]
50	10 h 15 min ± 0 h 41 min[b]	142.6 ± 12.5[d]	679.2 ± 16.8[f]
100	6 h 16 min ± 0 h 26 min[c]	142.9 ± 12.6[d]	339.7 ± 8.5[g]

[a-g]Groups within a variable not connected by the same superscript letter are statistically significantly different (Tukey Multiple Comparison; $P < 0.001$).

involved ideal arches, surface registration analysis, or linear measurements, which do not necessarily reflect standard clinical assessment of orthodontic models.

The American Board of Orthodontics (ABO) Cast-Radiograph Evaluation (CRE) grading system was developed from 1994 to 1999 as an objective method for the evaluation of treatment outcomes of cases presented for the clinical exam.[14] Cast stone traditionally served as the standard medium for models, but the ABO recently accepted 3D-printed models as a part of final records in the clinical examination. Although the ABO recently announced plans for a transition from a case-based clinical examination to a scenario-based examination,[15] the CRE grading system will likely continue to be used by the clinical and research communities for various applications, including, but not limited to, posttreatment case evaluation. Accordingly, as orthodontists increasingly embrace these digital technologies, investigation of the effects of printing parameters on the perception of 3D-printed models presents merit toward informing the clinical and research communities when making decisions on purchasing printers, in-office digital and 3D-printing workflows, and envisioned applications of printed parts. The objective of the present study was to investigate the effect of print layer height on the assessment of 3D-printed orthodontic models with the use of the ABO CRE grading system. The null hypothesis was that there is no significant difference in the CRE scores of models 3D printed at 25-, 50-, or 100-μm layer thicknesses and that there is no significant difference in the CRE scores of the 3D-printed models from any of the 3 print layer thicknesses compared with traditional stone models.

MATERIAL AND METHODS

Twelve sets of final orthodontic models (cast in stone) that were previously submitted for and passed the ABO clinical exam were scanned with the use of an R700 desktop scanner (3Shape, Copenhagen, Denmark) to form master stereolithography (STL) files. The study protocol was determined to qualify for exempt status according to 45 CFR 46.101(b) by the Institutional Review Board of the University of Texas Health Science Center at Houston (HSC-DB-17-0064). The scanner, which has been previously shown to be a reliable tool for creation of a digital file from a physical model,[16] was calibrated before scanning the plaster models. Each arch was scanned separately, resulting in 24 separate STL files. All models were scanned in the same orientation, base-down, which corresponded with the print orientation to be used. The models were then scanned with their opposing arch in occlusion. All models were properly trimmed with ABO bases. All digital files were unaltered before printing.

STL files corresponding to the dental models were loaded into PreForm software (v 2.11.1; Formlabs, Somerville, Mass), oriented so that the cusp tips were facing away from, and the base attached to, the build platform, and were evenly distributed across the build platform. All STL files for the stone models were then 3D printed with the use of different layer heights (25, 50, and 100 μm) in a Form 2 SLA printer (Formlabs) in a gray photopolymer resin (FLGPGR03; Formlabs). The applied orientation resulted in the model being printed layer by layer from the base to the cusp tips. All models from the 50- and 100-μm groups were arranged such that 2 sets of models (ie, 2 maxillary and 2 corresponding mandibular arches) were printed at a time for a given layer height. Six of the model sets from the 25-μm group were printed successfully in the same way, with 2 sets of models printed at a time. However, 2 consecutive print failures involving part delamination were observed when printing the next 2 sets of models from the 25-μm group. The remaining 6 model sets from the 25-μm group were printed 1 set at a time to overcome the issue, and no further print failures were observed. To enable standardized comparison of basic printing metrics across groups, the print time, resin volume, and number of layers associated with printing each of the 12 model sets (1 set at a time) at each of the 3 layer heights investigated (25, 50, and 100 μm) were calculated in PreForm software individually for each model set, with the model orientation as used in the printing and the layout as determined automatically

Table II. Two-tailed Pearson correlation coefficients of stone models with models of each 3D-printed layer height (25, 50, and 100-μm) for all ABO CRE metrics and total score

Metric	*25 μm*	*50 μm*	*100 μm*
Alignment/rotations	0.910*	−0.938*	0.349
Marginal ridges	0.531*	−0.475*	0.304
Buccolingual inclination	0.880*	−0.696*	−0.916*
Overjet	0.725*	−0.820*	−0.833*
Occlusal contacts	0.949*	−0.904*	−0.947*
Occlusal relationships	0.447*	0.190	−0.585*
Interproximal contacts	0.827*	−0.592*	−0.913*
Root angulation	0.717*	−0.723*	−0.776*
Total	0.829*	−0.926*	−0.961*

Values were computed based on averages across times and graders.
*$P < 0.05$.

Table III. Two-tailed Pearson correlation coefficients of the 3D-printed models among the investigated layer heights for all ABO CRE metrics and total score

Metric	*25 vs 50 μm*	*50 vs 100 μm*	*25 vs 100 μm*
Alignment/rotations	−0.897*	−0.532*	0.415
Marginal ridges	−0.867*	−0.836*	−0.846*
Buccolingual inclination	−0.760*	−0.635*	−0.919*
Overjet	−0.748*	−0.783*	−0.895*
Occlusal contacts	−0.908*	−0.878*	−0.948*
Occlusal relationships	0.363	0.264	−0.691*
Interproximal contacts	−0.483*	−0.581*	−0.941*
Root angulation	−0.892*	−0.873*	−0.917*
Total	−0.912*	−0.980*	−0.923*

Values were computed based on averages across times and graders.
*$P < 0.05$.

by the software. The average associated print times, resin volumes, and number of layers with associated standard deviations are reported in Table I. In total, 72 arches were printed to create 36 sets of orthodontic models (n = 12 per layer height).

After the completion of each print, the models were separated from the build platform and washed in accordance with instructions from the manufacturer.[17] Briefly, the models were agitated in an immersion bath of 2-propanol for 2 minutes, left to rest in the same bath for 8 more minutes (10 total minutes), and then moved to another immersion bath to rest for 10 minutes. The models were left to air dry at room temperature for at least 1 hour. The bottoms of the bases of the models were then labeled with unique identifiers, with A, B, and C corresponding to 50, 25, and 100 μm, respectively.

All 4 sets of models (plaster and 25-, 50-, and 100-μm) from each case (n = 12) were scored by 4 ABO-certified graders (faculty) and 7 residents, who had been trained and calibrated with the use of the CRE grading tool and grading criteria.[18] All models were scored by each grader a second time at least 2 weeks later. Models were graded in random orders, and the labels were coded to reduce bias. Each grader also scored at both times the root angulation with the use of a panoramic radiograph associated with each case. All scores were recorded by the individual graders using the ABO CRE worksheet,[19] and were subsequently compiled in a spreadsheet for analysis.

Statistical analysis

A generalized linear mixed model (GLMM), implemented in R statistical software (R Core Team, 2017) using the *glmer* function of the *lme4* package was used to evaluate effects of print layer height on each of the CRE grading metrics, as well as total score. The model controlled for random effects of time (different grading sessions), dental model (each individual case), each individual grader, and grader type (faculty or resident) while evaluating the fixed effect of print layer height on a given response variable.

A Pearson correlation coefficient (PCC) was used to evaluate correlation between scores of each of 8 model grading criteria (alignment/rotations, marginal ridges, buccolingual inclination, overjet, occlusal contacts, occlusal relationships, interproximal contacts, and root angulation) and the total scores between stone models and models printed at 25, 50, and 100 μm. A PCC was also used to evaluate correlations between 3D-printed models of the various layer heights. All values were based on averages across both time points and across all graders. All P values were 2 sided, and P values < 0.05 were considered to be significant.

RESULTS

The GLMM showed no statistically significant effects of print layer height on the ABO scoring of the models for any of the grading metrics or total score.

Although no statistically significant effects of print layer height were found in the GLMM analysis, PCC analysis was applied to provide additional information regarding the correlations of stone models with 3D-printed models of each layer height (Table II), and correlations between the 3D-printed models themselves (Table III). All 3D-printed models were, at minimum, highly positively correlated with the stone models for occlusal contacts and total score and, at minimum, moderately positively correlated for all other metrics except alignment/rotations and marginal ridges in the 100-μm group and occlusal relationships in the 50-μm

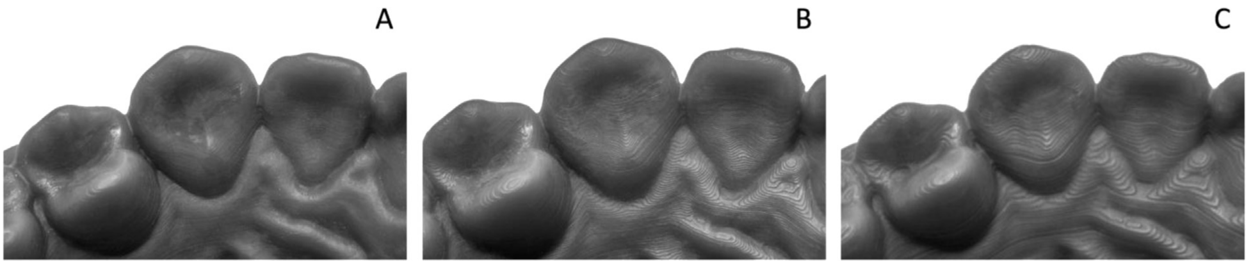

Fig. Close-up view of the surfaces of models printed with (A) 25-μm, (B) 50-μm, and (C) 100-μm layer heights.

group. All 3D-printed models were, at minimum, highly positively correlated with each other for marginal ridges, overjet, occlusal contacts, and total scores and, at minimum, moderately positively correlated with each other for all other metrics except alignment/rotations (25- vs 100-μm group) and occlusal relationships (25- vs 50-μm group and 50- vs 100-μm group).

DISCUSSION

The objective of this study was to investigate the effect of print layer height on the clinical acceptability of 3D-printed models with the use of the ABO CRE grading system as an objective treatment outcomes measure and traditional orthodontic plaster models as the criterion standard. Because of the clinical relevance of the ABO CRE grading criteria, this information could aid clinicians in the decision-making process when considering the purchase and use of in-office 3D printers. It is generally accepted that the ABO CRE grading criteria make the evaluation of orthodontic treatment outcomes, especially as related to parallel roots, well articulated models, and functional occlusion, more objective than visual observation alone.[20] Therefore, we applied the grading system in our aim of determining the clinical relevance of the impact of layer height of 3D-printed models on the perception of these 3D-printed models.

A Form 2 SLA printer (Formlabs, Inc., Somerville, MA) using a gray photopolymer resin (FLGPGR03, Formlabs) was applied in the study because of the low cost and high reported accuracy.[9] The Form 2 and other comparable printers have become popular among private practice orthodontists for the production of models in-house for various applications, including, but not limited to, clear aligner fabrication. The base-down, cusp tip-up, print orientation was also chosen for its reported accuracy.[11] The gray photopolymer resin was selected for its matte finish in compliance with the ABO Digital Model and 3D Printing Requirements. The guidance document also speaks to color requirements, although gray is not specifically mentioned.[21] The impact of color on evaluation of 3D-printed models could be the subject of future investigation.

As discussed by Favero et al, x- and y-axes in the chosen print orientation refer to those that are parallel to the build platform, with the z-axis representing the build direction, which is perpendicular to the build platform.[9] Higher resolution in the z-axis is a function of decreased layer height, resulting in a theoretically smoother surface of the 3D-printed model with greater anatomic detail. Therefore, the smaller the layer height, the smoother the surface of the model will appear in the z-direction and the smaller the distance between layers lines observed on diagonal surfaces.[17] In the selected print orientation, the layer lines are apparent on cusp tips, incisal edges, and occlusal grooves, because layers are laid down perpendicular to the occlusal surface in those regions (Fig). This surface detail, however, is also affected by the diameter of the UV-curing laser and the radical polymerization kinetics that define SLA printing, as well as any uncured resin remaining after post-printing processing.[22]

Print layer height showed no significant effects on the response variable of each individual CRE metric or total score. Because the CRE grading system assigns values of 0, 1, or 2 when scoring the models, the scores were considered as count data. Furthermore, the individual metric data followed a Poisson distribution rather than a normal distribution. Because the means of the individual metrics totaled less than 5, statistical elucidation of difference between groups (if any) is limited. However, the means of total scores were, on average, around 20 and normally distributed. Because of this, the model was very robust for elucidation of statistically significant effects of print layer height on total score from the CRE grading system (Table IV).

The 100-μm layer height 3D-printed models in the present study were most strongly correlated with stone models for buccolingual inclination, overjet, occlusal relationships, interproximal contacts, and total score and were least correlated for alignment/rotations and marginal ridges (Table II). Buccolingual inclination and

Table IV. Mean ± standard deviation scores for each ABO CRE metric and the associated total score across graders and times

Metric	*Stone*	*25 μm*	*50 μm*	*100 μm*
Alignment/ rotations	4.3 ± 1.9	4.4 ± 2.0	4.0 ± 2.2	4.2 ± 2.2
Marginal ridges	3.8 ± 1.5	3.3 ± 1.6	3.3 ± 1.7	3.1 ± 1.6
Buccolingual inclination	4.1 ± 2.0	4.2 ± 2.0	4.1 ± 2.2	4.0 ± 2.1
Overjet	1.3 ± 1.3	1.4 ± 1.5	1.3 ± 1.4	1.3 ± 1.4
Occlusal contacts	2.0 ± 1.8	2.0 ± 1.9	1.9 ± 1.9	2.0 ± 1.9
Occlusal relationships	3.8 ± 2.0	3.4 ± 2.0	3.6 ± 2.2	3.5 ± 2.1
Interproximal contacts	0.2 ± 0.4	0.1 ± 0.3	0.2 ± 0.6	0.1 ± 0.4
Root angulation	2.1 ± 1.3	2.2 ± 1.5	2.2 ± 1.4	2.2 ± 1.4
Total	21.6 ± 4.3	20.9 ± 4.5	20.6 ± 4.8	20.4 ± 4.5

occlusal relationships are graded based on discrete anatomic regions, namely cusp tips, which are likely to be most easily visualized in this layer height due to the more defined layer lines leading to the cusp tips, which appear similar to a terraced topographic map (Fig). For ease of understanding, visualize discerning the peak of a rolling hill versus a terraced hill. It is easier to pick a defined point that represents the highest elevation on the terraced peak.

Overjet is graded in the anterior region based on any contact of the incisal edges of the mandibular anterior teeth with the lingual surface of the maxillary anterior teeth. In the posterior region, overjet is graded based on the relationship of the buccal cusps of the posterior mandibular dentition with the fossae of the maxillary arch. At smaller layer heights in the selected print orientation, more layers are placed on the incisal edges of anterior teeth, resulting in a theoretically smoother surface (Fig). Smoother surfaces, as appear on the 25-μm layer height models, may lead the grader to perceive that there are areas of no contact, leading to extra points on the CRE grading. Furthermore, more layers could result in more material in certain areas, as well as more errors, leading to a weaker correlation with stone. Contacts on the lingual surface of the maxillary anterior teeth were easier to see on the 100-μm layer height models, resulting in a greater correlation with the stone models.

The marginal ridge and alignment/rotations criteria are graded in areas of diffuse anatomy, which can be most affected by surface detail, or lack thereof, resulting in low correlation of the 100-μm layer height 3D-printed models with the stone models. As an example, consider if there is more material on the mesiobuccal and less on the distobuccal line angles of any particular tooth, particularly mandibular premolars, than exists on the stone cast. This phenomenon could potentially occur as a result of the algorithms that determine when an area should be printed or not, based on the chosen layer heights. In this example, a mesial-out malrotation could be interpreted on a 3D-printed model that is not represented on the stone model. The impact of layer height on the anatomy of occlusal grooves could also affect the grading of alignments and rotations in the maxillary posterior segments. As a result, greater deviation is observed in CRE scores for 3D-printed models of larger layer heights for this metric. For marginal ridges, if the 100-μm layer height model had a layer cut off on one tooth but added on the neighboring adjacent tooth based on the printing parameters, the difference could vary as much as 0.15 mm from the 25-μm models (0.075 mm difference × 2 areas = 0.15 mm total). This discrepancy could turn a 0.4-mm difference in marginal ridge height on a 25-μm layer height model, which would not be scored, into a 0.55-mm difference on the 100-μm layer height model, which would result in a point scored on the CRE form.

Interproximal contacts, in the print orientation investigated, are least affected by layer thickness because they are formed as a function of the x- and y-axes, and not the vertical z-axis. As previously discussed, accuracy of prints in the XY-plane is a function of the diameter of the UV curing laser and the radical polymerization kinetics that define SLA printing.[22] Models printed with a 25-μm layer height have a 4-fold increase in the number of layers relative to corresponding 100-μm layer height models, and the greater the number of layers printed, the greater the potential error.[17] More errors on prints of lower layer heights could lead to the appearance of closed interproximal contacts on the 3D-printed models that are perceived as being open on the stone models, if errors were in a positive direction. Finally, differential presentation of tooth anatomy, associated with differing layer heights, could result in varying amounts of uncured resin retained on the surfaces of the printed models. Uncured resin most commonly pools, owing to capillary action, in areas of discrete detail, such as interproximal contacts and occlusal grooves, potentially leading to the weaker correlation in the grading of interproximal contacts for models printed at lower layer heights.

Many of the observed differences in correlation were minor. For example, stone models were very highly correlated with each of the 25-, 50-, and 100-μm layer height 3D-printed models for occlusal contacts (r values 0.949, 0.904, and 0.947, respectively; $P < 0.01$). Furthermore, 3D-printed models of all layer heights were very highly correlated with one another ($P < 0.01$) for all metrics, except for alignment/rotations (between 25- and 100-μm groups) and occlusal relationships (between 25- and 50-μm groups and between 50- and 100-μm groups). These similarities may be explained in the use of a clinically relevant grading method on models of layer thicknesses that varied below reported clinical tolerances. The nominal difference in 100- and 25-μm layer height prints is 0.075-mm per layer, and previous sources have cited the threshold for clinical relevance as ranging from 0.2 to 0.5 mm.[6-8] Accordingly, differences in layer height in the print orientation investigated would be expected to have minimal effect on the clinical acceptability of the 3D-printed models.

A few limitations were recognized in the study. First, although the ABO CRE grading system was used as an objective grading system, there is still a modicum of subjectivity. All graders evaluated panoramic radiographs associated with each case and assigned values for root angulation, a metric unaltered by physical models. Pearson correlation coefficient values for 25-, 50-, and 100-μm layer height 3D-printed models (0.717, 0.723, and 0.776, respectively) were not equal to 1.0 in relation to stone models for root angulation, reflecting the subjectivity associated with the grading system (Table II). In addition, this study design compared models printed from a single printer type using a digital workflow. There are errors in each step of the workflow process, as well as with different printers and printing methods. Future studies could evaluate the effects of various other printers, printing formats, and workflows.

CONCLUSIONS

1. At the chosen orientation and on the SLA-format printer used, the 100-μm layer height models were most highly correlated with the criterion-standard orthodontic stone models for total score, buccolingual inclination, overjet, occlusal relationships, and interproximal contacts.
2. Because of a lack of statistically significant effects of print layer height (25, 50, and 100 μm) on the CRE grading of 3D-printed models, 100-μm layer height 3D-printed models are potentially clinically acceptable for the purposes of evaluation of treatment outcomes, diagnosis and treatment planning, and residency training. Furthermore, they are recommended due to decreased associated print times.

ACKNOWLEDGMENTS

The authors thank Ruby Benjamin-Gardner for assistance with statistical analysis. They also thank the residents who participated in the grading of the models: Katie Camacho, Peyton Cometti, Lindsey Lyons, Suzanna Nida, Anika Rodgers, and Jon Scott.

REFERENCES

1. Verweij JP, Jongkees FA, Anssari Moin D, Wismeijer D, van Merkesteyn JPR. Autotransplantation of teeth using computer-aided rapid prototyping of a three-dimensional replica of the donor tooth: a systematic literature review. Int J Oral Maxillofac Surg 2017;46:1466-74.
2. Ahamed SF, Kanna ASA, Kumar RKV. 3D-printed orthodontic auxiliaries. J Clin Orthod 2015;5:337-41.
3. Bae GS, Kim SS, Park SB, Son WS. 3D-printed double-wire bracket for anterior alignment. J Clin Orthod 2017;7:377-81.
4. Hazeveld A, Huddleston Slater JJ, Ren Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. Am J Orthod Dentofacial Orthop 2014;145:108-15.
5. Kasparova M, Grafova L, Dvorak P, Dostalova T, Prochazka A, Eliasova H, et al. Possibility of reconstruction of dental plaster cast from 3D digital study models. Biomed Eng Online 2013;12:49.
6. Halazonetis DJ. Acquisition of 3-dimensional shapes from images. Am J Orthod Dentofacial Orthop 2001;119:556-60.
7. Hirogaki Y, Sohmura T, Satoh H, Takahashi J, Takada K. Complete 3-D reconstruction of dental cast shape using perceptual grouping. IEEE Trans Med Imag 2001;20:1093-101.
8. Schirmer UR, Wiltshire WA. Manual and computer-aided space analysis: a comparative study. Am J Orthod Dentofacial Orthop 1997;112:676-80.
9. Favero CS, English JD, Cozad BE, Wirthlin JO, Short MM, Kasper FK. Effect of print layer height and printer type on the accuracy of 3-dimensional printed orthodontic models. Am J Orthod Dentofacial Orthop 2017;152:557-65.
10. Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. Am J Orthod Dentofacial Orthop 2018;153:144-53.
11. Short MM, Favero CS, English JD, Kasper FK. Impact of orientation on dimensional accuracy of a 3D printed orthodontic model. J Clin Orthod 2018;52:13-20.
12. Camardella LT, de Vasconcellos Vilella O, Breuning H. Accuracy of printed dental models made with 2 prototype technologies and different designs of model bases. Am J Orthod Dentofacial Orthop 2017;151:1178-87.
13. Wan Hassan WN, Yusoff Y, Mardi NA. Comparison of reconstructed rapid prototyping models produced by 3-dimensional printing and conventional stone models with different degrees of crowding. Am J Orthod Dentofacial Orthop 2017;151:209-18.
14. Casko JS, Vaden JL, Kokich VG, Damone J, James RD, Cangialosi TJ, et al. American Board of Orthodontics: objective grading system for dental casts and panoramic radiographs. Am J Orthod Dentofacial Orthop 1998;114:589-99.
15. Chung CH, Tadlock LP, Barone N, Pangrazio-Kulbersh V, Sabott DG, Foley PF, et al. American Board of Orthodontics: time for change. Am J Orthod Dentofacial Orthop 2018;153:321-3.
16. Lemos LS, Rebello IM, Vogel CJ, Barbosa MC. Reliability of measurements made on scanned cast models using the 3

Shape R 700 scanner. Dentomaxillofac Radiol 2015;44: 20140337.
17. Formlabs. What does resolution mean in 3D printing? Pt. 3. 2016: Available at: https://formlabs.com/blog/layer-height-meaning-3dprinting/. Accessed January 25, 2018.
18. American Board of Orthodontics. The American Board of Orthodontics grading system for dental casts and panoramic radiographs. 2012: Available at: https://www.americanboardortho.com/media/1191/grading-system-casts-radiographs.pdf. Accessed January 25, 2018.
19. American Board of Orthodontics. ABO Cast-Radiograph Evaluation 2010: Available at: https://www.americanboardortho.com/media/1184/cast-radiograph-worksheet-for-print.pdf. Accessed January 25, 2018.
20. Schabel BJ, McNamara JA, Baccetti T, Franchi L, Jamieson SA. The relationship between posttreatment smile esthetics and the ABO objective grading system. Angle Orthod 2008;78:579-84.
21. American Board of Orthodontics. Digital model and 3D printing requirements. 2018: Available at: https://www.americanboardortho.com/media/1157/abo-digital-model-requirements.pdf. Accessed January 25, 2018.
22. Formlabs. What does resolution mean in 3D printing? Pt. 2. 2016: Available at: 2016. https://formlabs.com/blog/horizontal-resolution-meaning-3d-printing/. Accessed January 25, 2018.