OPEN

PRS GLOBAL OPEN

IDEAS AND INNOVATIONS

Pediatric/Craniofacial

Dimensional Error in Rapid Prototyping with Open Source Software and Low-cost 3D-printer

Marco A. Rendón-Medina*
Laura Andrade-Delgado†
Jose E. Telich-Tarriba‡
Antonio Fuente-del-Campo†
Carlos A. Altamirano-Arcos‡

Summary: Rapid prototyping models (RPMs) had been extensively used in craniofacial and maxillofacial surgery, especially in areas such as orthognathic surgery, posttraumatic or oncological reconstructions, and implantology. Economic limitations are higher in developing countries such as Mexico, where resources dedicated to health care are limited, therefore limiting the use of RPM to few selected centers. This article aims to determine the dimensional error of a low-cost fused deposition modeling 3D printer (Tronxy P802MA, Shenzhen, Tronxy Technology Co), with Open source software. An ordinary dry human mandible was scanned with a computed tomography device. The data were processed with open software to build a rapid prototype with a fused deposition machine. Linear measurements were performed to find the mean absolute and relative difference. The mean absolute and relative difference was 0.65 mm and 1.96%, respectively ($P = 0.96$). Low-cost FDM machines and Open Source Software are excellent options to manufacture RPM, with the benefit of low cost and a similar relative error than other more expensive technologies. *(Plast Reconstr Surg Glob Open 2018;6:e1646; doi: 10.1097/GOX.0000000000001646; Published online 25 January 2018.)*

BACKGROUND

Rapid prototyping employs computer-aided design. In the field of medicine, Mankovich et al.[1] were the first to describe the use of additive manufacturing for the creation of anatomical models with stereolithography (STL).

Rapid prototyping models (RPM) had been extensively used in craniofacial and maxillofacial surgery,[1–14] especially in areas such as orthognathic surgery, posttraumatic or oncological reconstructions, and implantology.[15] The applications of 3D printing technology are varied and include preoperative planning, the creation of templates to guide the surgeon transoperatively, as well as the production of implants or surgical instruments previously designed for each patient.[5,6,8,10,11,14] Kumta et al.[6] described 9 clinical cases where RPMs were implemented. They summarize the benefits of RPM in improving communication between medical experts and patients, facilitating customization of treatment devices, aiding the production of surgical implants, improving surgical planning, orienting aid device during surgery, enhancing diagnostic quality, preoperative simulation, and simple exposition of the surgery plan to the patients and to prepare a template for resection.[6] Malagon et al.[2] described the application of RPM in STL in planning surgical correction of hypertelorism. They reported that these models give the surgeon space realism and physical capacities to plan the surgery, facilitating the surgery and possibly improving the surgeon performance.[2]

Because the technologies in the 1990s have been developed for the creation of RPM, each with its advantages and indications, the most commonly used techniques are STL, selective laser sintering (SLS), and fused deposition modeling (FDM).[1] STL is by far the most common technique used for RPM in our field, as it allows for the production of smooth and high-resolution models. However, its main disadvantage relates to the costs associated with the materials, as well as the hardware and software required to create each RPM.[16]

*From the *Department of General Surgery, Hospital General de México "Dr. Eduardo Liceaga," Mexico City, Mexico; †Department of Plastic and Reconstructive Surgery, Hospital General "Dr. Manuel Gea Gonzalez" Mexico City, Mexico; and ‡Department of Plastic Surgery, Hospital General "Dr. Manuel Gea Gonzalez," Mexico City, Mexico.*

Received for publication November 7, 2017; accepted December 4, 2017.

All sources were acquired with a private budget. None of the authors profit by marketing or using any of the software or hardware used during the manufacture of rapid prototyping models.

DOI: 10.1097/GOX.0000000000001646

Disclosure: *The authors have no financial interest to declare in relation to the content of this article. The Article Processing Charge was paid for by the authors.*

Economic limitations are higher in developing countries such as Mexico, where resources dedicated to health care are limited, therefore limiting the use of RPM to few selected centers. Recently, owing to the expiration of several patents, new low-cost FDM printers have been marketed worldwide, offering potential clinical applications. These printers and the materials employed currently lack FDA approval for any purpose. However, we believe that physicians and patients could benefit by using generic 3D printers and open source software to print low-cost RPM.[2–4,6,14,17–23] The description of the technical production of RPM with low cost could encourage other centers to produce their own RPM.

Nizam et al.[8] stated that the main determinants of dimensional error are the quality of the CT scan and the rapid prototype machine. To ensure high clinical quality and precision of any RPM, validation of the manufacture processes is highly advised.[3,4,7,8,10,11,18,19,24] This article aims to determine the dimensional error of a low-cost FDM 3D printer (Tronxy P802MA, Shenzhen, Tronxy Technology Co), with open source software.

METHODS

An ordinary dry human mandible from the anatomical collection of the Plastic and Reconstructive Division of the Hospital General "Dr. Manuel Gea Gonzalez" was scanned with a computed tomography device (Phillips Scanner, mx16EVO2) by placing it on the scanner's surface with the Frankfort plane parallel to the table. The radiological protocol was as follows: 120 kV, 100 mA, slice thickness of 1 mm.[25,26] The image was stored in Digital Imaging and Communications in Medicine (DICOM) format.

The DICOM was exported to 3D-Slicer version 4, open source software (Brigham and Women's Hospital, Inc, Boston, Mass.) to generate a Standard Triangle Language Format file. Then, the Standard Triangle Language Format data were exported to the Repetier Host open source software (Willich, Germany) to generate G programming language (G-code).

The RPM was printed using the Tronxy P802MA printer (Shenzhen, Tronxy Technology Co), a machine based on FDM; 1.75 mm polylactic acid (PLA) filament was used as raw material. The model was created using 2 mm layers, with extruder temperature at 200°C, bed heated at 60°C. Total printing time was 6.5 hours and required 25 g of PLA.

We used the Ibrahim et al.[27] landmarks and linear measurements to determine the absolute and relative dimensional error (Fig. 1). Two independent evaluators performed measurements in 25 separate occasions for each linear measure to reduce interobserver variability to 20% of error, based on the Cantor equation.[28]

All the data analysis was performed with R-Studio open source software (R-Studio, Boston, Mass.). Mean and SD were used to perform descriptive and statistical analysis with Student's t test for 2 samples with $P < 0.01$.[27] Absolute dimensional error and relative dimensional error were calculated as per previous validation studies.[5,8,15,19,22,25–27,29]

The linear measurements were classified into 2 groups to evaluate observer precision and Cohen Kappa's index. Each measurement was subtracted from the mean value if the result was < 0.05 mm; it was assigned to group 1 and when greater to group 2.

Formulas:

$$Absolute\ difference\,(cm) = prototype\ value - dry\ mandible\ value$$

$$Relative\ difference = \frac{prototype\ value - dry\ mandible\ value}{dry\ mandible\ value} x100$$

RESULTS

We performed a total of 650 measurements and calculated the mean absolute and relative differences: 0.65 mm and 1.96%, respectively. The statistical analysis showed a P value of 0.96, concluding that there is no significant difference in the mean values. The mean of each linear measure was analyzed separately, showing that 7 of the 13 linear measurements had a statistical difference to the dry mandible, but when evaluating the mean of all, no difference was found.

We evaluated the precision of each evaluator, each measurement against the mean of them. Evaluator 1 had a precision in measurements < 0.05 mm of 44.61% (N = 290), and evaluator 2 had a precision 11.07% (N = 72) of the 650 different measurements. Interobserver variability was evaluated by Cohen's Kappa index with the value of 0.4 (0.3–0.4), an acceptable value in medical sciences.[30]

DISCUSSION

Multiple authors have reported validation studies comparing RPM with dry anatomical structures. Asaumi et al.[25] conducted a validation protocol in dry cranial models with coronoid hyperplasia. They created STL models and reported a dimensional error of approximately 2%, very close to the results we found, a dimensional error of 1.96%. We must add that they stated that the models in their study had a mean cost of about 1,300 USD each. PLA costs between USD 20 and 60 per kilogram, and the 3D-printer under US 1,000. So with the money invested in 1 STL model, technically you could build several FDM models, with an equivalent dimensional error.

In another validation article, Nizam et al.[8] described the dimensional error in STL skull models more effectively. They reported the absolute difference of 0.23 mm with a dimensional error of 0.08%. They report more precise models than our study but it is well known that STL has a better resolution than FDM models.[27] The cost of FDM may outweigh the STL high-resolution; further clinical trials should explore this possibility.

Silva et al.[26] explored the dimensional error of SLS technology and 3D-printing; they studied skull segments against the SLS models. They reported a dimensional error of 2.10% for SLS and 2.67%. Skulls are more complex anatomic structures than mandibles, explaining why the augmented dimensional error in contrast with our findings in mandibles.

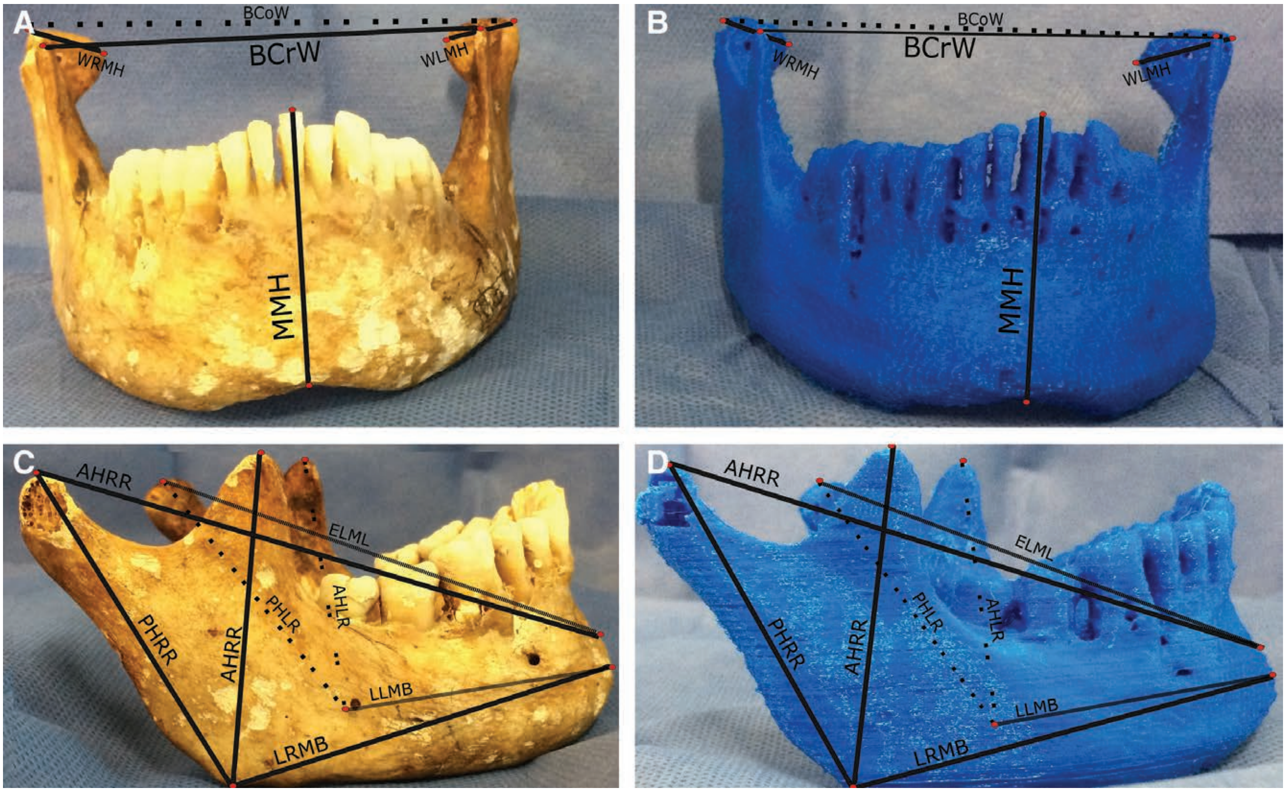

Fig. 1. Linear measurements on the dry mandible. Dry mandible to the left (A and C) and RP to the right (B and D).

Ibrahim et al.[27] compared 3 technologies, SLS, 3DP, and PolyJet, in their models. They reported dimensional errors of SLS 1.79%, PloyJet 2.14%, and 3DP 3.14%. We based our protocol of linear measurements on their work. So, the comparison of their findings with ours is very valuable. They reported a cost of each model around USD 150 for the 3DP, USD 250 for SLS, and USD 350 for the PolyJet model, in contrast with the price of a single model in FDM with low-cost printers and open source software that costs ≅ USD 10.

Petropolis et al.[31] evaluated FDM models against STLs of a dry skull and a mandible. They used a Cube X (3dSystems, Rock Hill, S.C.), which has a relatively elevated cost, in contrast to other available machines. They used different resolution in the printer settings, 100, 250, and 500 ɥm; they reported a dimensional error of 0.44%, 0.53%, and 1.1%. On the other hand, they used only 7 linear measurements, of which just 2 corresponded to the mandible, probably explaining the high accuracy of the models in contrast with other researchers.

Maschio et al.[19] conducted a study evaluating dimensional error of a low-cost FDM printer different from the one used in our study. They reported a dimensional error of 3.76%, but they used different linear measurements than we did. They evaluated teeth position and reported the greatest dimensional error presented in the literature. They indicated that 8 of the 13 linear measures they used were actually smaller than 12 mm, explaining the difference between their findings and other studies.

CONCLUSIONS

Nowadays, multiple companies are offering FDM low-cost 3D printers with increasing resolution and quality. We have reported here a dimensional error similar to that of more expensive technologies, but at a meager cost. Open source software was not explored in the application of rapid prototyping, reducing the cost of manufacturing anatomic models with clinical applications. Our low-cost protocol has similarly acceptable dimensional errors in comparison with other technologies.

We can conclude that low-cost FDM machines and open Source Software are excellent options to manufacture RPM, with the benefit of low cost and a relative error similar to that of more expensive technologies. The clinical applications are, principally but not reduced to, surgical planning. Currently, in the Hospital Manuel Gea Gonzalez, this technology has been applied to osteogenic mandibular distraction and other surgical plans.

Marco Aurelio Rendón-Medina, MD
Hospital General de México "Dr. Eduardo Liceaga"
Doctor Balmis 148, Z.C. 06720
Mexico City, Mexico
E-mail: dr.rendon1989@gmail.com;
md_marm@hotmail.com

ACKNOWLEDGMENTS

The authors extend their gratitude to the Department of Specialized Radiology, Hospital General "Dr. Manuel Gea Gonzalez" *especially to M.D. Talia N. Chargoy-Loustaunau and M.D. Nidia Escobar-Hernandez, for their help and support in acquiring the DICOM data for this article.*

REFERENCES

1. Mankovich NJ, Cheeseman AM, Stoker NG. The display of three-dimensional anatomy with stereolithographic models. *J Digit Imaging.* 1990;3:200–203.
2. Hidalgo HM, Romo GW, Estolano RT. Stereolithography: a method for planning the surgical correction of the hypertelorism. *J Craniofac Surg.* 2009;20:1473–1477.
3. Bouyssié JF, Bouyssié S, Sharrock P, et al. Stereolithographic models derived from x-ray computed tomography. Reproduction accuracy. *Surg Radiol Anat.* 1997;19:193–199.
4. Kang SH, Lee JW, Lim SH, et al. Validation of mandibular genioplasty using a stereolithographic surgical guide: *in vitro* comparison with a manual measurement method based on preoperative surgical simulation. *J Oral Maxillofac Surg.* 2014;72:2032–2042.
5. Chang PS, Parker TH, Patrick CW Jr, et al. The accuracy of stereolithography in planning craniofacial bone replacement. *J Craniofac Surg.* 2003;14:164–170.
6. Kumta S, Kumta M, Jain L, et al. A novel 3D template for mandible and maxilla reconstruction: rapid prototyping using stereolithography. *Indian J Plast Surg.* 2015;48:263–273.
7. Kragskov J, Sindet-Pedersen S, Gyldensted C, et al. A comparison of three-dimensional computed tomography scans and stereolithographic models for evaluation of craniofacial anomalies. *J Oral Maxillofac Surg.* 1996;54:402–411; discussion 411.
8. Nizam A, Gopal RN, Naing L, et al. Dimensional accuracy of the skull models produced by rapid prototyping technology using stereolithography apparatus. *Arch Orofac Sci.* 2006;1:60–66.
9. Sarment DP, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. *Int J Oral Maxillofac Implants.* 2003;18:571–577.
10. Barker TM, Earwaker WJS, Lisle DA. Accuracy of stereolithographic models of human anatomy. *Australas Radiol.* 1994;38:106–111.
11. Berry E, Brown JM, Connell M, et al. Preliminary experience with medical applications of rapid prototyping by selective laser sintering. *Med Eng Phys.* 1997;19:90–96.
12. Zhang N, Liu S, Hu Z, et al. Accuracy of virtual surgical planning in two-jaw orthognathic surgery: comparison of planned and actual results. *Oral Surg Oral Med Oral Pathol Oral Radiol.* 2016;122:143–151.
13. Gateno J, Allen ME, Teichgraeber JF, et al. An *in vitro* study of the accuracy of a new protocol for planning distraction osteogenesis of the mandible. *J Oral Maxillofac Surg.* 2000;58:985–990; discussion 990.
14. Meakin JR, Shepherd DET, Hukins DWL. Fused deposition models from CT scans. *Br J Radiol.* 2004;77:504–507.
15. Olszewski R, Szymor P, Kozakiewicz M. Accuracy of three-dimensional, paper-based models generated using a low-cost, three-dimensional printer. *J Craniomaxillofac Surg.* 2014;42:1847–1852.
16. Legocki AT, Duffy-Peter A, Scott AR. Benefits and limitations of entry-level 3-dimensional printing of maxillofacial skeletal models. *JAMA Otolaryngol Head Neck Surg.* 2017;143:389–394.
17. Chen H, Yang X, Chen L, et al. Application of FDM three-dimensional printing technology in the digital manufacture of custom edentulous mandible trays. *Sci Rep.* 2016;6:19207.
18. El-Katatny I, Masood SH, Morsi YS. Error analysis of FDM fabricated medical replicas. *Rapid Prototyp J.* 2010;16:36–43.
19. Maschio F, Pandya M, Olszewski R. Experimental validation of plastic mandible models produced by a “low-cost” 3-dimensional fused deposition modeling printer. *Med Sci Monit.* 2016;22:943–957.
20. Agrawal, Karoon A. Cleft palate repair and variations. *Indian J Plast Surgery.* 2009;42:102–109.
21. Xiao Y, Sun X, Wang L, et al. The application of 3D printing technology for simultaneous orthognathic surgery and mandibular contour osteoplasty in the treatment of craniofacial deformities. *Aesthetic Plast Surg.* 2017:1–12.
22. Salmi M, Paloheimo KS, Tuomi J, et al. Accuracy of medical models made by additive manufacturing (rapid manufacturing). *J Craniomaxillofac Surg.* 2013;41:603–609.
23. Santler G, Kärcher H, Ruda C. Indications and limitations of three-dimensional models in cranio-maxillofacial surgery. *J Craniomaxillofac Surg.* 1998;26:11–16.
24. Reynolds M. 3-D volumetric evaluation of human mandibular growth. *Open Biomed Eng J.* 2011;5:83–89.
25. Asaumi J, Kawai N, Honda Y, et al. Comparison of three-dimensional computed tomography with rapid prototype models in the management of coronoid hyperplasia. *Dentomaxillofac Radiol.* 2001;30:330–335.
26. Silva DN, Gerhardt de Oliveira M, Meurer E, et al. Dimensional error in selective laser sintering and 3D-printing of models for craniomaxillary anatomy reconstruction. *J Craniomaxillofac Surg.* 2008;36:443–449.
27. Ibrahim D, Broilo TL, Heitz C, et al. Dimensional error of selective laser sintering, three-dimensional printing and PolyJet models in the reproduction of mandibular anatomy. *J Craniomaxillofac Surg.* 2009;37:167–173.
28. Cantor AB, Lee H. Sample-size calculations for Cohen’s kappa. *Psychol Methods.* 1996;l:150–153.
29. Choi JY, Choi JH, Kim NK, et al. Analysis of errors in medical rapid prototyping models. *Int J Oral Maxillofac Surg.* 2002;31:23–32.
30. McHugh ML, Herbohn J, Clendenning J, et al. Interrater reliability: the kappa statistic. *Biochem Medica.* 2012;22:276–282.
31. Petropolis C, Kozan D, Sigurdson L. Accuracy of medical models made by consumer-grade fused deposition modelling printers. *Plast Surg (Oakv).* 2015;23:91–94.