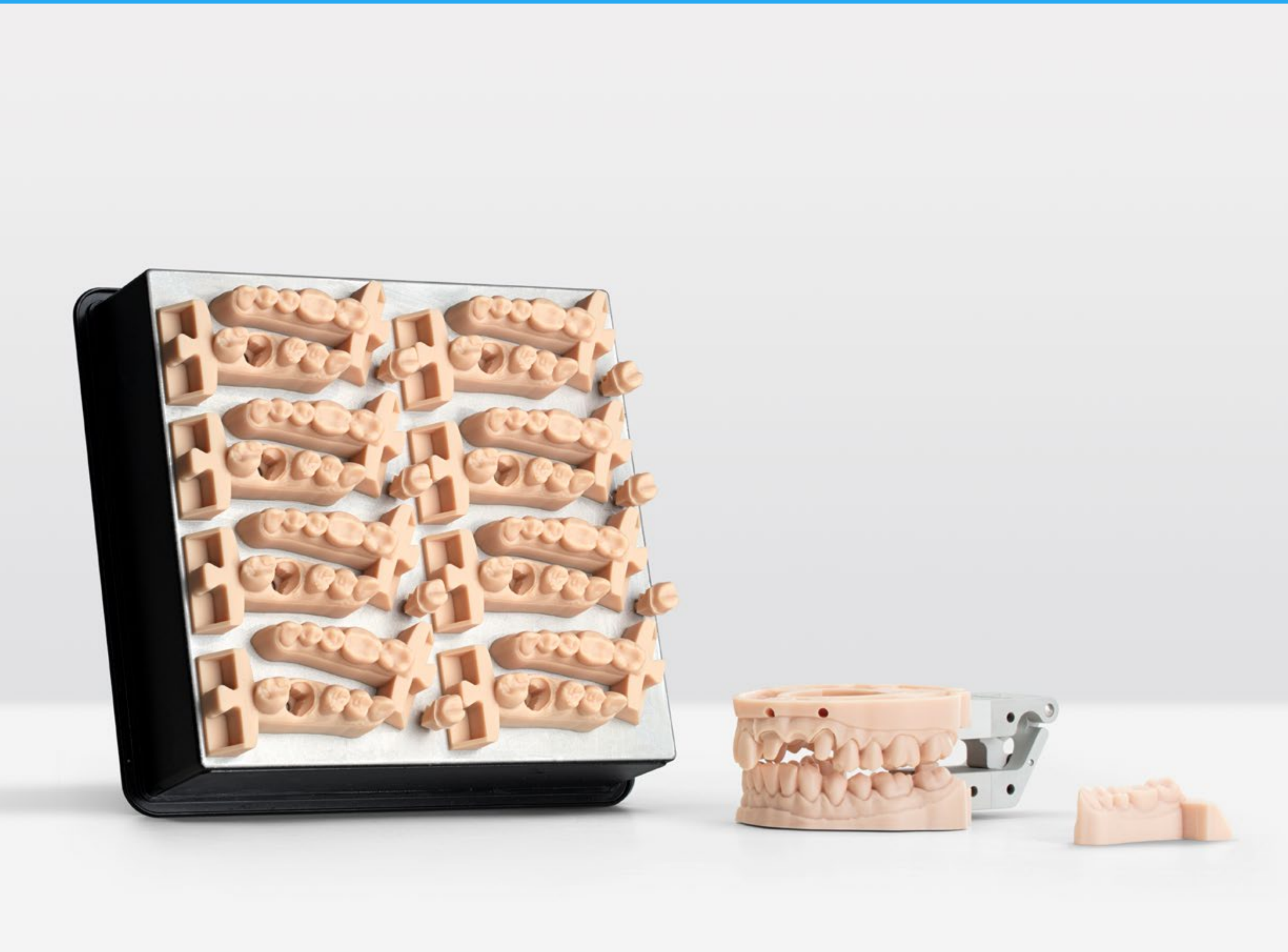

FORMLABS WHITE PAPER:

Digital Dental Model Production with High Accuracy 3D Printing

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Table of Contents

Abstract 3

About the Author 3

Introduction 4

Accuracy and Precision in 3D Printing 5

Defining Clinical Accuracy Needs for Dental Models 6

Clinical Accuracy 7

Tactile Evaluation Methods 8

Optical Evaluation Methods 8

Translating Clinical Benchmarks to Print Specifications 9

Evaluating 3D Printing Accuracy 10

Methodology 10

Results 11

Case Study: Mandibular Ceramic Crown 12

Comparisons to Other 3D Printing Systems 13

Conclusion 15

References 16

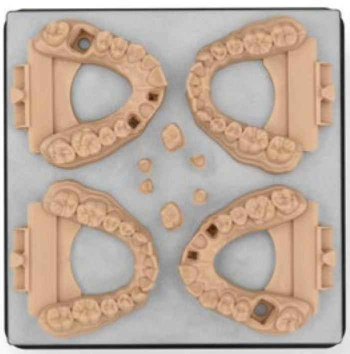
Learn More 17

Abstract

Practicing clinical dentistry requires the extensive use of accurate replicas of patients' oral dentition and tissues. Digital methods of fabricating these models, such as 3D printing, have become prevalent as a solution to many of the problems associated with traditional production methods. Until recently, high-accuracy 3D printing has been synonymous with large-format, high-cost machines. However, with the advent of advanced desktop 3D printing technology, clinicians are adopting additive manufacturing as a cost-efficient, scalable tool for introducing and expanding digital model fabrication workflows. I worked closely with Formlabs to establish clinically relevant benchmarks in order to perform an accuracy study using its Dental Model Resin on the Form 2 desktop stereolithography (SLA) 3D printer. The results of the study demonstrate that Formlabs Dental Model Resin is able to produce high-accuracy removable die models with the precision and consistency required for successful clinical procedures. Additionally, we fabricated models on the Form 2 with Dental Model Resin in a case study to test the fit of a mandibular ceramic crown, which was successfully fitted on a patient.

About the Author

Michael Scherer, DMD, MS is an assistant clinical professor at Loma Linda University, a clinical instructor at University of Nevada – Las Vegas, and maintains a practice limited to prosthodontics and implant dentistry in Sonora, California. He is a fellow of the American College of Prosthodontists, has published articles, DVD training series, and full-online courses related to implant dentistry, clinical prosthodontics, and digital technology with a special emphasis on implant overdentures. As an avid technology and computer hobbyist, Dr. Scherer's involvement in digital implant dentistry has led him to develop and utilize new technology with CAD/CAM surgical systems, implement interactive CBCT implant planning, and outside of the box radiographic imaging concepts. Dr. Scherer also maintains five YouTube channels: "LearnLOCATOR," "LearnLODI," "LearnSATURNO," "LearnLOCATOR F–Tx" and "The 3D Dentist" — popular YouTube channels on dental implant procedures and digital dentistry. He also runs a 3D printing blog and in-person and online courses for 3D printing (www.michaelschererdmd.com).



Introduction

With intraoral scanning techniques having tremendously improved clinical dentistry practices and the accuracy of impression procedures,[1-4] the advent of affordable high-accuracy 3D printing technology represents a watershed moment within the dental industry. The ability to reliably and consistently produce highly accurate restorations within a private dental office or small dental laboratory can solve many of the problems associated with traditional techniques,[4-5] and yield significant savings in production time and costs.

In order to deliver such change, it's instrumental that clinicians to be able to trust that models printed on a 3D printing system are precise and accurate. Being able to manually test the feel and fit of physical models, just like those generated with traditional methods of model fabrication, is an essential step in the dental workflow. It is integral to the success of a final procedure.

Until recently, most of the professional 3D printing market consisted of expensive, large-format 3D printers, with high machine costs limiting access to large dental labs. In contrast, advanced desktop 3D printers, such as Formlabs' Form 2, have garnered considerable interest for producing models in-house for dental labs and even clinical practices of all sizes.

Introducing cost-efficient, scalable 3D printing in-house allows for a smooth transition to fully digital, streamlined workflows that quickly allow return on investment. However, in order to effectively assess which printing technology to invest in, it is crucial to verify accuracy.

Therefore, using Formlabs Dental Model Resin and a large set of Form 2 3D printers, we set out to demonstrate that a desktop 3D printing system could accurately and repeatedly produce crown and bridge models with removable dies to acceptable clinical standards. An accuracy study was performed using Formlabs Form 2 3D printers and Formlabs Dental Model Resin.

In this paper, we first define accuracy and precision, to establish what specific print performance we are trying to characterize. We then establish the relevant benchmarks a dental model must achieve to be clinically acceptable, extensively examining literature and previously conducted studies. Following this, we describe the accuracy study that was carried out to characterize print performance, and examine the results to conclude whether Formlabs' Form 2 is capable of producing highly-accurate dental models, suitable for clinical practice. Finally, we outline a case study in which models were printed on the Form 2 using Dental Model Resin, and used to test the fit of a mandibular ceramic crown, which was then successfully fitted on a patient.

Accuracy and Precision in 3D Printing

In order to achieve meaningful 3D print performance for any application, both accuracy and precision must be considered. Accuracy is the closeness of a measurement to true value. Precision measures the repeatability of a measurement — in other words, consistency and repeatability. It is imperative that both an acceptable level of accuracy and a high level of precision are achieved.

What level of accuracy or precision is needed in dental 3D printing applications? To answer this, we examined common practice, published literature, and previously conducted studies. We then established a meaningful specification for what performance to expect from a dental 3D printer.

Defining Clinical Accuracy Needs for Dental Models

For a dental model to be effective for checking restorations such as crowns or bridges, it is critical that it can be used to check the marginal adaptation of the restoration. A good marginal fit is key to the long term clinical success of the restoration. Large marginal gaps can negatively impact acceptance rates of restorations, potentially leading to decay and premature loss of the restoration.

It is critical, therefore, that a dental model accurately and precisely reproduce the cervical line, also known as the margin line, of a restoration. In addition, for a dental model to be used for large multi-unit restorations, it is also critical to achieve an acceptable level of accuracy across the entire model. We therefore defined two measures by which to evaluate the accuracy of dental models:

MARGIN ACCURACY The accuracy with which the margin line, and die surfaces above the margin line, are reproduced.

GLOBAL ACCURACY The accuracy overall of the model, measured across a full arch.

To gauge the clinical needs for each of these specifications, we examined the techniques used in common clinical practice, as well as published literature and previously conducted studies.

Clinical Accuracy

Accuracy of the clinical fit of a restoration, such as a ceramic crown, inlay, or implant prosthesis, is usually established via a subjective analysis performed by a clinician or laboratory technician. This analysis is principally determined by visual methods, such as using a radiographic/X-ray image or disclosing media; alternating finger pressure; one-screw test; screw-resistance test; and dedicated digital instruments, or tactile methods, such as using a physical instrument, performed directly with the restoration fitting the tooth or implant.

A tremendous amount of variability within this approach is evident within dentistry. While many clinicians commonly assert that restorations should fit with marginal adaptation discrepancies within 10-30 µm, studies by Christensen evaluating this request indicated that, in practice, clinicians accepted a range between 34 µm and 119 µm of crown mis-fit at the gingival margins.[6] Furthermore, nearly half the clinicians were found to be inconsistent with their evaluation methods; sometimes the same clinician will reject the fit of a restoration that they accepted earlier.

While many methods have been advocated throughout the years, the two gold-standards of proper restoration fit within clinical dentistry are: tactile feel with an explorer instrument and visual assessment with a radiograph image.

Pictured left are two examples of very similar three-unit implant fixed partial dentures. Both show clinically acceptable restorations, but with no marginal discrepancy (left), and a slight, clinically acceptable marginal discrepancy (right).

TACTILE EVALUATION METHODS

Many clinicians utilize instruments, such as a dental explorer, to make decisions regarding the clinical fit of a restoration. Clinicians use the explorer instrument to “feel” over the restoration; if the instrument catches a groove near the margin, clinicians would reject the restoration, indicating that it wouldn’t properly fit. Using scanning electron microscopy, Rappold showed that the new, unused explorer tip is 68 μm thick, ultimately indicating that many clinicians may accept a restoration misfit of up to that amount.[7] In addition, many clinicians do not routinely sharpen or purchase new equipment for each patient, thus potentially accepting increased levels of restoration misfit.

An explorer is used to assess clinical fit of a restoration by using tactile feel of the instrument passing contours of the teeth. As the tip of the instrument slides into grooves or depressions on the tooth/restoration surface, it gives the clinician the ability to assess the clinical fit of a restoration.

OPTICAL EVALUATION METHODS

Radiographic assessment of dental restoration fit is an important method, used both by clinicians and also by third-party payors, such as dental insurance plans. Radiographic assessment utilizes a conventional dental X-ray generated image of the side, or proximal, portions of the dental crown to confirm the edges of the tooth preparation are meeting the margins of the restoration. While this method of assessment of clinical fit is subjective, it does offer a high degree of predictability between clinicians. It is, however, highly dependent upon angulation of the radiograph; increasing the angle decreases reliability. Angulation of the radiograph ±10 degrees in a vertical plane can result in clinicians potentially missing open margins or result in a restoration misfit of 100 μm.[8] As radiographic angulation approaches 20 degrees, this misfit can increase to as much as 700 μm.

Many clinicians rely upon a dental mirror to assess clinical fit of a restoration, visually inspecting to see if there is any marginal discrepancy.

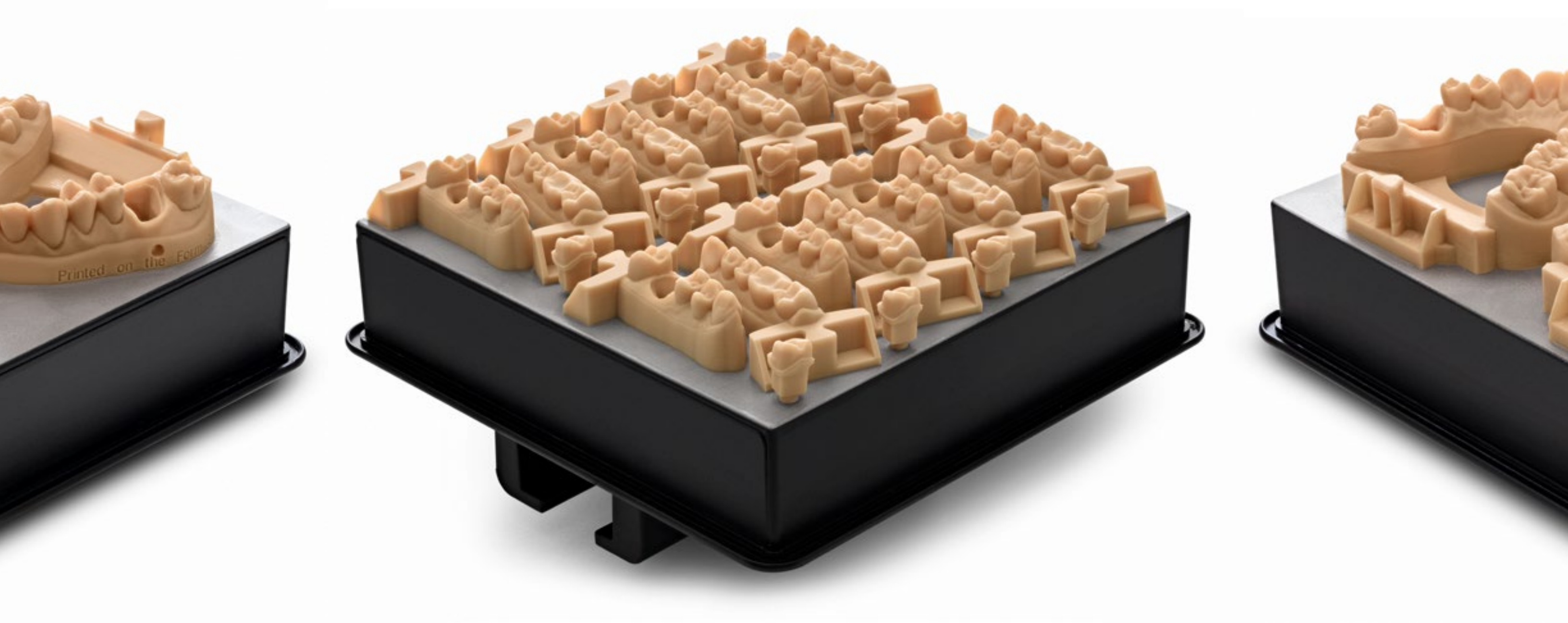
Taking many of these factors into consideration, research has established that in practice, the fit discrepancy of a restoration considered acceptable is between 50 – 200 µm.[8] Based upon many factors mentioned within this section, there is a general consensus that an average clinician would consider 100 µm the maximum acceptable discrepancy for a crown, implant, or restoration which "fits."[8]

Translating Clinical Benchmarks to Print Specifications

Based upon these benchmarks for clinical acceptability, we returned to our three measures of accuracy. With general clinical acceptability of a margin gap of up to 100 µm, an accuracy range of less than half of this would be an acceptable range, i.e., ±50 µm. For contact points, an equivalent range of ±50 µm would also be relevant. Across a full arch, i.e., a distance ranging from 40-60 mm, an aim of ±100 µm was chosen. Expressed as a proportion, this would represent ±0.25 percent to ±0.17 percent.

Figure 1. Clinical Benchmarks for Margin and Global Accuracy

	Clinically Relevant Aim
Margin Accuracy	±50 µm
Global Accuracy	±100 µm



Evaluating 3D Printing Accuracy

METHODOLOGY

We set out to evaluate the accuracy and precision of 3D printed crown and bridge models with removable dies on the Form 2 using Dental Model Resin, the highest accuracy resin in the Formlabs resin library. As accuracy is material dependent, this choice was deliberately made to see the best possible results.

A total of 148 parts — a variety of die and arch models — were printed directly on the build platform. After printing, each part was removed from the build platform, cleaned with isopropyl alcohol (IPA), post-cured for 60 minutes at 60 C° in a UV cure chamber, and optically scanned using a 3Shape D900L desktop scanner. Each model scan was compared to its original .STL file using Convince Analyzer (3Shape).

Accuracy tolerances corresponding to the 80th surface percentile were measured. Surface percentiles represent the proportion of points on the surface of interest that are within a given distance from the nominal, i.e., desired, position. Thus an accuracy tolerance of ±38 µm for the 80th surface percentile translates to 80 percent of the surface being within ±38 µm of the nominal surface.

This process was performed over a representative set of six different Form 2 printers. Using a broad set of Form 2 printers allows us to comment on the population as a whole — on the precision of the machine — rather than just performance on one machine.

Figure 3. Accuracy of Print to 3D Model: Margin Lines and Die Surfaces.

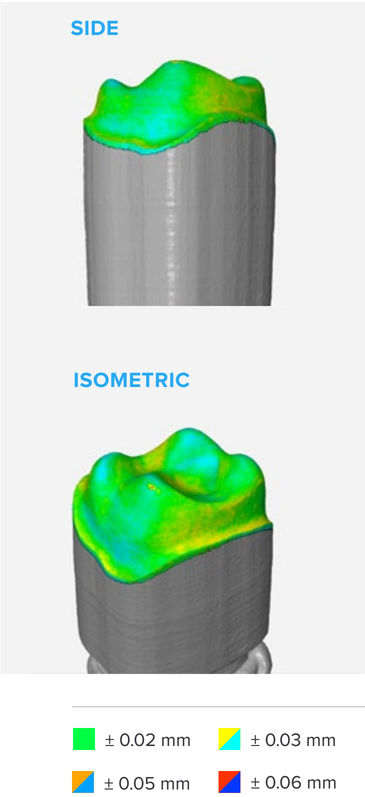
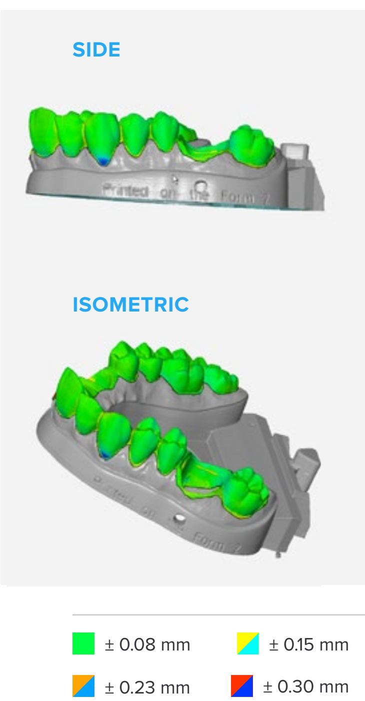


Figure 4. Accuracy of Print to 3D Model: Full Arch



RESULTS

Figure 2. Margin and Global Accuracy Results

	Reference Object	Clinically Relevant Aim	80th Percentile Results		
			100 Micron Print Settings Results (±μm)	**50 Micron Print Settings Results (±μm)**	**25 Micron Print Settings Results (±μm)**
Margin Accuracy	Removable Die	±50 μm	±64.2 μm	±44.7 μm	±30.5 μm
Global Accuracy	Full Arch Model	±100 μm	±149.6 μm	±104 μm	±67.9 μm

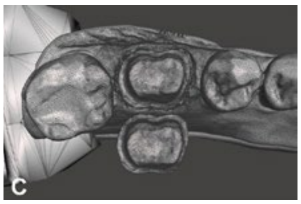
The results of the study provide strong evidence that printing at 50 micron or 25 micron settings will yield clinically acceptable models.

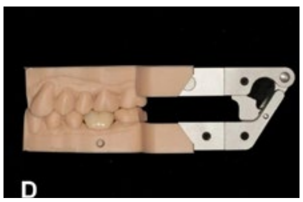
At 100 micron layer thicknesses, margin and global accuracy results were outside of our initially defined bounds. However, considering the variability in clinical acceptance and testing methods, it is interesting to note that these are likely within a range that would be clinically acceptable for many users.

At 50 micron print settings, the margin accuracy fell within our defined aim for margin accuracy, and the global accuracy measured across the sample dataset fell just outside the range at ±104 μm. Taking into account the standard deviation of these measurements, this is virtually in range, and is likely of zero clinical significance. Therefore it is evident that printing at 50 micron layer thicknesses will achieve acceptably accurate models for crown and bridge model purposes.

At 25 micron settings, the highest level of accuracy is achieved, both in terms of margin and global accuracy. While achieving high performance metrics like this may be attractive to some clinicians, it is important to note that these are far beyond the initially defined aims, and the difference in performance between printing at 25 micron and 50 micron settings is likely of zero clinical significance.

This pattern of increased accuracy when printing at thinner layer thicknesses is due to the way 3D models discretize into layers for a 3D printer to print. When a part has any angled edges, which are not directly on the Z-axis or XY plane, the thickness of the layers determines the number of discrete points the edges of the part hit. Fewer, thicker layers result in a stepping effect — creating longer distances between discrete points. Many thin layers result in smoother, more detailed surfaces, which will hit more discrete points, and therefore measure closer to the scan, making the part more accurate.





Case Study: Single Ceramic Crown

A 52-year-old patient presented the concern that he “chipped one of the back molars.” A clinical examination revealed a fractured disto-lingual cusp on lower right first molar (tooth #30) (A). A radiograph was made confirming no caries were present and the patient requested a ceramic crown.

Topical and local anesthetic was placed. The crown was sectioned and removed utilizing a diamond bur and gentle manipulation. The preparation was refined, the cord was placed, and an optical impression was made (B). The optical impression system allows the clinician to reliably fabricate a digital model of the patient’s preparation, dentition, and surrounding soft tissues. Further, scans of the opposing and bite were completed (C). The digital files were sent to a dental laboratory for further procedures. A provisional material was fabricated, cemented, and the patient was scheduled for the crown-seat procedure.

The files were received and the models were imported and designed using dental CAD software. Three files were generated: 1) a model of the opposing dentition, 2) a model of the preparation with a recess corresponding to a ditched die, and 3) a model of the ditched die of the preparation (D-F). Each file was individually printed on a Form 2 3D printer using Dental Model Resin on 50 micron layer thickness settings. Each of the models were finished using Formlabs’ Finish Kit, with staged rinsing in 91 percent isopropyl alcohol (IPA) followed by UV curing in a industrial curing machine.

The models were printed with articulator features (D), allowing the laboratory technician to physically articulate the models and verify occlusion of the restoration. A pressed lithium disilicate crown was fabricated and fitted to the model, verifying contacts to adjacent teeth (E) and marginal integrity (F).

The patient returned for final clinical procedures. No anesthetic was required, the provisional was removed, and the preparation was cleaned prior to bonding. The restoration was tried in, verifying contacts, marginal adaptation, and aesthetics. Using the established dental industry workflows combined with Formlabs Dental Model Resin, minimal adjustments were required, as the restoration fit with incredible precision. The crown was luted using resin cement (G-H) and a radiograph was made to verify that all of the cement was properly removed (I). Occlusion was verified and the restoration was polished. The patient was extremely comfortable and very pleased with his new restoration.

Comparisons to Other 3D Printing Systems

These results cover only the Formlabs Form 2 3D printer, providing evidence of how a desktop 3D printing system can achieve the highest levels of clinically relevant performance in printing dental models. However, these results do not speak more broadly about the print performance of other desktop 3D printers, nor of dental 3D printers in general.

Therefore, we sought to compare results against other 3D printers. This is an inherently difficult problem, made more difficult by the lack of a common standard for comparing printers.

One common misrepresentation of accuracy is the descriptions of XY resolution as accuracy. For digital light processing (DLP), XY resolution is the projected pixel size. Many 3D printer systems use this projected pixel size, or XY resolution as the overall accuracy figure — for example taking a 75 micron projected pixel size and asserting that the accuracy of the machine is ±75 microns.

This data has no implications for how accurate a printed part will be. There are many sources of error that still have an impact on accuracy, from components, to calibration, to part shrinkage post-printing, to others.

Ultimately, as outlined in our study, the most effective, scientific method for testing accuracy and precision is through printing and measuring real printed parts. In order to measure precision, and to be statistically significant, a large sample size of parts, and a representative sample of machines, must be used.

With limited resources, this study was unable to complete such a wide-ranging comparison. However, to get an initial sense of how the results from this study on the Form 2 might compare with other 3D printing systems, we sought to do a comparison of actual print performance against two established large-format 3D printers, one costing $35,000, the other costing $75,000. With each system, we printed an identical part on both the Form 2 and the system being compared.

Results from both tests showed that print results on the Form 2 were virtually indistinguishable from either system, in terms of accuracy. Given limited resources and time, only two reference model was compared with each, so the statistical significance of this is limited. However, it does provide evidence that suggests that, in terms of accuracy, the Form 2 performs just as well as these established large-format systems.

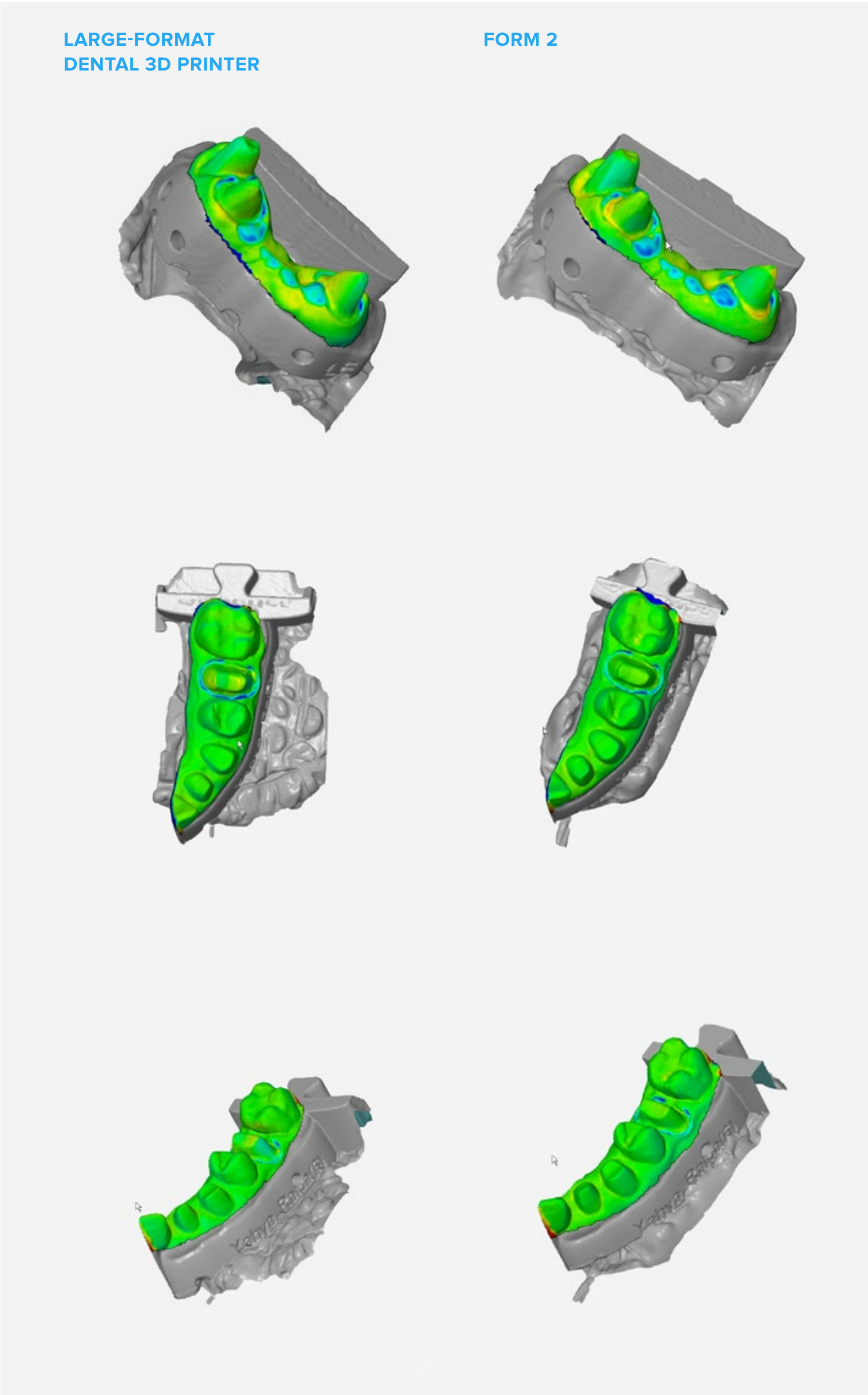


Figure 5. Accuracy of Print to 3D Model Comparison

We scanned and printed two models (the first in row 1, the second in rows 2 and 3) on both an established large-format dental 3D printer used in a dental lab today (shown in the left-hand column) and on the Formlabs Form 2 (shown in the right-hand column). As pictured in the difference heat map, the accuracy achieved by each print is nearly identical. The large-format printer costs approximately $75,000, while the Form 2 costs $3,499.

± 0.08 mm
± 0.15 mm
± 0.23 mm
± 0.30 mm

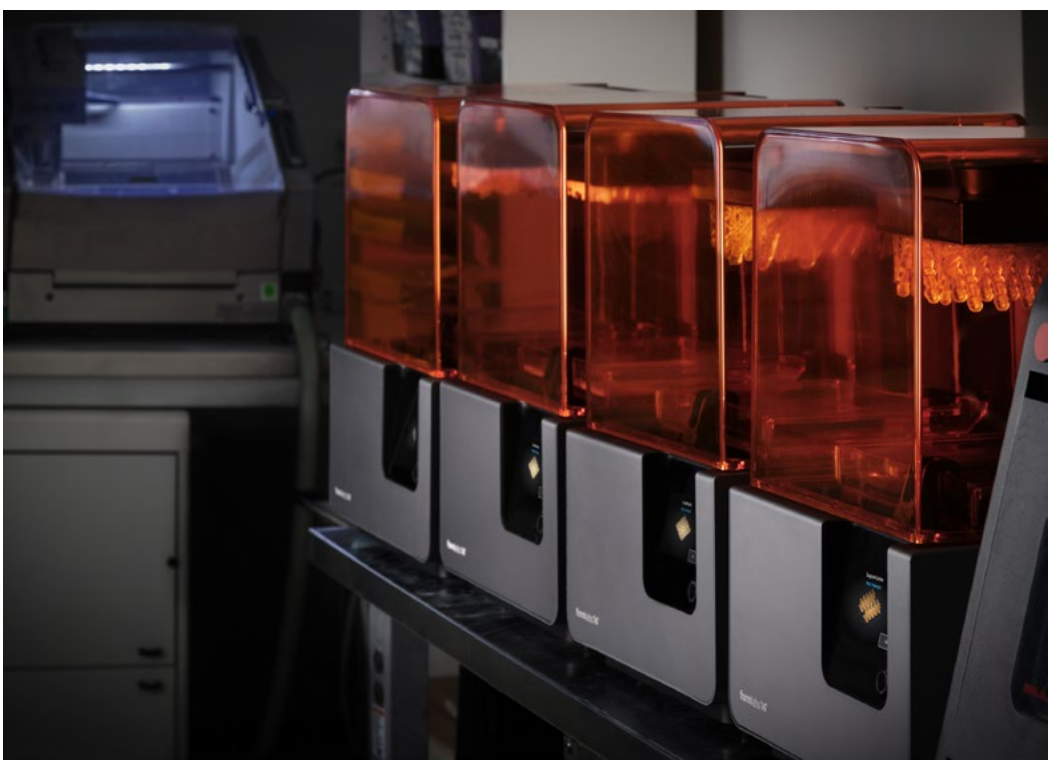
Conclusion

The growth in adoption of affordable, desktop 3D printing systems offers the potential for major change in the dental industry. The potential for such printers to be used to reliably print dental models for checking high accuracy restorations provides significant opportunity to reduce production times and costs.

The results of this study demonstrate that it is possible to produce highly-accurate, precise dental models with removable dies on the Formlabs Form 2 with Dental Model Resin. Prints made at 50 micron and 25 micron layer thicknesses on a representative sample of Form 2s are well within the range of clinically relevant accuracy, both in terms of accuracy of the margin line and die surface, as well as global accuracy.

A small comparison with two large-format 3D printers also provided evidence that Form 2 print performance is indistinguishable from systems already accepted and adopted by dental labs. A more in-depth comparison involving larger volumes of prints and a representative sample of both desktop and industrial 3D printing systems would be necessary to draw broader conclusions from a direct comparison of 3D printing systems.

The capability to produce high accuracy dental models in-house, to the necessary clinical standards, represents a huge opportunity for dental professionals of all kinds, solving many of the problems associated with traditional production methods, and breaking previous barriers to adopting digital fabrication.



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