The Accuracy of 3D Printing Technology: A Comparison of Additive Manufacturing Processes

by

Ezra I. Merritt
Lieutenant Commander, Dental Corps
United States Navy

A thesis submitted to the Faculty of the
Prosthodontic Graduate Program
Naval Postgraduate Dental School
Uniformed Services University of the Health Sciences
in partial fulfillment of the requirements for the degree of
Master of Science
in Oral Biology

June 2018

MASTER'S THESIS

Is to certify that the Master's thesis of

Author
Ezra I. Merritt Dental Corps, U.S. Navy

The Examining Committee for the thesis requirement
Degree in Oral Biology at the June 2018 graduation.

Glen Imamura, DDS, MS
Research Committee Chair

[redacted]

Anton Petrich, DDS, MS
Graduate Program Director- Prosthodontics

[redacted]

Daniel Ellert, DDS, MS
Research Mentor
Prosthodontics Chief, Removable Partial Dentures

The author hereby certifies that the use of any copyrighted material in the thesis manuscript titled:

"The Accuracy of 3D Printing Technology: A Comparison of Additive Manufacturing Processes"

is appropriately acknowledged and, beyond brief excerpts, is with the permission of the copyright owner.

RESIDENT SIGNATURE

[redacted]

Resident Name
[Specialty Department] Graduate Program
Naval Postgraduate Dental School
DATE

NAVAL POSTGRADUATE DENTAL SCHOOL
Author

2018

Distribution Statement

Distribution A: Public Release.

ABSTRACT

Introduction- Digital technology has been transforming the field of dentistry since the early 1970's. Computer Aided Design/ Computer Aided Manufacturing (CAD/ CAM) has vastly improved since that time, and can often allow a completely digital workflow in the treatment of dental patients. Three- dimensional (3D) printing is an additive manufacturing technology that minimizes the amount of material waste and improves the ability to better capture the internal anatomy of an object when compared to subtractive manufacturing (milling). As 3D printing technology improves and becomes more cost effective, it will become more prevalent in the field of dentistry.

Objective- To compare the accuracy and precision of full arch dental models fabricated by different 3D printers.

Materials & Methods- A dental model was scanned using a laboratory scanner to produce an STL file. This STL file was then utilized to produce 10 models on the 3Dent EnvisionTEC, Bego Varseo and Projet 5000 printers for a total of 30 models. Each of the 30 models were then scanned to produce individual STL files to compare back to the original master STL using 3matic software. An average overall mean and standard deviation was collected for each of the 30 comparisons. An average overall mean and standard deviation was collected for each of the 30 comparisons.

Results- 3Dent produced a mean difference of 79.8 micrometers +/- a standard deviation of 13.0, Bego produced an absolute mean difference of 65.5 micrometers with a standard deviation of +/- 7.8, and Projet 5000 produced an absolute mean

difference of 75.5 micrometers with a standard deviation of +/- 23.2. A One-way ANOVA revealed a P value equal to 0.146, therefore no statistically significant difference was found between the three printers.

Conclusion- The Bego Varseo produced a lower overall mean than the other two printers, however the difference was not clinically significant.

INTRODUCTION

The use of additive manufacturing is well documented in the automotive, aerospace, and defense industries.[1] In dentistry, 3 dimensional (3D) printed models are now used predictably for treatment planning, pre-surgical models and surgical guides. As the precision and accuracy of this technology continues to improve, it will become more pervasive throughout all sectors of healthcare. Presently, stone casts remain the standard for most dental laboratory procedures. As the price of additive manufacturing continues to decrease and materials improve, there may be a trend away from the traditional stone model. Has 3D printing technology reached the level of accuracy that is required to fabricate clinically acceptable dental restorations? The objective of this study is to compare the accuracy of the 3 Dent (EnvisionTec), Varseo (Bego), and Projet 5000 (3D Systems) to a gold standard.

REVIEW OF THE LITERATURE

A search was conducted of current and historical literature using the following key terms: "3D printing", "additive manufacturing", "3D printing accuracy", "additive manufacturing in dentistry" using PUBMED and Clinical Key.

Much of the recent literature discusses the use of additive manufacturing for applications within the field of medicine and dentistry. Outside of surgical guides for implant placement or surgical planning models, there is a lack of literature relating 3D printing to the level of accuracy required in the field of Fixed Prosthodontics. The goal of this research is to answer the research question, has 3D printing reached the level of accuracy required to challenge more conventional approaches to fixed prosthodontics?

PRINCIPLES OF ADDITIVE MANUFACTURING

Three-dimensional printing has also been referred to as "additive manufacturing" and "rapid prototyping." This particular manufacturing modality is gradually becoming more popular than its predecessor, subtractive manufacturing. The American Society for Testing Materials (ASTM) defines additive manufacturing as, "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."[2] Alternatively, subtractive manufacturing implies a drilling or milling process where material is removed.

"The STL file is the standard for every additive manufacturing process." STL stands for Standard Tessellation Language or Stereolithography. This term refers to the file creation process that converts a geometric or 3-dimensional image within a computer-aided design (CAD) file into small triangles or coordinates.[3] This process has varying levels of accuracy, depending on the manufacturer or system. The smaller the triangles, the greater the accuracy.

There are at least eighteen methods of additive manufacturing, with several modifications within select methods.[1] The most common and widely used are: stereolithography (SL), Polyjet fused deposition modeling (FDM), laminated object manufacturing (LOM), 3D printing (3DP), selective laser sintering (SLS), laminated engineered net shaping (LENS), and electron beam melting (EBM) (Wong, 2012).

Stereolithography was the first and remains the most commonly used additive manufacturing modality. This process involves a liquid-based photosensitive polymer being cured in layers when exposed to an ultraviolet laser.[3] As each successive layer is cured, the platform is lowered to continue the build process.[3] After completion of the curing process, the excess liquid is drained and can be reused.[3] A layer thickness of less than 10 microns can be achieved when using this process.[3]

Polyjet FDM utilizes a thin plastic filament that feeds a machine where a print head melts the material and extrudes it in small layers. "Materials used in this process are polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyphenysulfone, PC-ABS blends, and PC-ISO, heating or a mix of metals with very different melting point."[3] The main advantage of this technique is the wide variety of materials that can be used. The unused powder can be recycled. Disadvantages include: accuracy is limited by the particle size of the material used, possibility of oxidation if proper inert gas atmosphere is not maintained, and the temperature must be maintained near the melting point.[4]

LOM combines concepts of both additive and subtractive manufacturing. The build material comes in sheet form and through a series of pressure, heat, and a thermal adhesive coating, the sheets are bonded together.[3] A carbon dioxide laser cuts the material based on the CAD and STL file.[3] This method is advantageous because of its lower cost. Also, no post processing or support structures are required during the fabrication stage.[3] Because subtractive manufacturing is included in the LOM process, there is wasted material, a decrease in surface definition, and difficulty with capturing complex internal anatomy.[3]

3DP describes a process in which a water-based binder is supplied via a jet a starch-based powder. The powder particles are glued together as the binder is jetted during the build process.[3] The process is very similar to the two-dimensional inkjet printing process. A large variety of polymers can be utilized.

Selective laser sintering (SLS) utilizes powders and a carbon dioxide laser for the build process. The chamber is heated to a temperature just below the melting temperature of the material and a piston lowers the platform, which contains the powders. The platform is lowered the same amount as the layer thickness each time a layer is completed.[3] A benefit to this method is the variety of materials that can be used such as plastics, combinations of metals, combinations of polymers and metals, and combinations of metals and ceramics.[3] Another advantage of SLS is any unused powder can be recycled. A potential disadvantage is the level of accuracy is limited by the particle size of the material used.

EBM is a process similar to SLS except a high voltage source is required to power an electron laser beam which is used to melt a metal powder.[3] This process is intended to build metallic parts only, and takes place in a high vacuum chamber to avoid oxidation. A propose future use for this technology would be in outer space since a high vacuum chamber is utilized.

Polyjet uses inkjet technologies to manufacture models. The head of the inkjet moves in the x and y axes, depositing the photopolymer, which is then cured via ultraviolet light. According to the literature, a layer thickness of 16 microns can be achieved.[3] A key advantage to this method is that parts of multiple colors can be built. A major disadvantage is that the parts produced are much weaker than those produce by other additive manufacturing options.[3]

APPLICATIONS OF ADDITIVE MANUFACTURING

Additive manufacturing applications are commonly found in healthcare. Its' use in medicine can be organized into several broad categories such as: customized prosthetics, implants, anatomical models, tissue and organ fabrication, manufacturing of surgical instruments, pharmaceutical drug fabrication, and medical device fabrication.[1] Dental applications include surgical guides and anatomical models used for treatment and surgical planning.

Bio-models are commonly printed for treatment planning purposes. Advances in transmission-based scanning methods such as Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) have provided clinicians a greater level of diagnostic accumen prior to performing an invasive procedure.[1] Three-dimensional printed replicas can mimic the size, weight and texture of organs or other vital structures allowing surgeons to rehearse complicated procedures.[4]

MATERIAL OPTIONS IN ADDITIVE MANUFACTURING

Polymers are the raw material used to build various programmed structures.[2] Examples of polymers used in additive manufacturing include thermoplastics, wax, and photo-initiated resins. Thermoplastic materials are used by fused deposition model (FDM) machines.[2] In this process, filaments of the thermoplastic material are heated and then extruded through a nozzle in order to build the structures.[2] Wax has been used as a support material, but also is utilized as a material to prepare models for more complex prosthodontic cases.[2] Photo-initiated resins are commonly utilized by Stereolithographic (SLA) machines. This material is cured one layer at a time and offers the benefit of greater variability in color and rigidity.[2] Light cure resins can be used to replace the manual wax-up step in the lost wax technique for casting metal restorations.[5]

ACCURACY OF CURRENT 3D PRINTING TECHNOLOGIES

Dentistry has benefited from the advances in digital technology. The standard bearer, however, remains dental stone and other analog techniques. Until 3D manufacturing can be proven to be as accurate as dental stone, 3D printing will remain inferior in many dental applications.

Hazeveld et al. (2014) compared the accuracy and reproducibility of 3D printed models to standard stone models.[6] The 3 rapid prototyping techniques evaluated were: digital light processing, jetted photopolymerization, and 3-dimensional printing. Twelve maxillary and mandibular plaster models were chosen at random to serve as gold standards. Each plaster model was scanned to obtain an STL file. Each file was converted into a physical models by one of the rapid prototyping techniques mentioned. A digital caliper was used to record linear measurements from several common points on each model for comparison to the same points on the "gold standard". Observers measured the clinical crowns of the teeth from first molar to first molar in both a mesial- distal direction as well as in a gingival-coronal direction. All models were measured five times with a two-week interval between measurements.

The absolute tooth-size discrepancy ranged between 0.00 mm and 1.24 mm in the anterior and from 0.03 mm to 2.26 mm overall. The difficulty mentioned by the authors was in identifying the predefined landmarks. The replica models used colored materials with a rough surface that made landmark identification more difficult. Further studies are needed to validate these finding. If there are discrepancies among models, one must further identify where they are occurring on the model. There were definite differences in accuracy identified among the various techniques.

A similar study by Lee et al. (2015) in the Korean Journal of Orthodontics utilized fifty extracted molar teeth and scanned each tooth to produce fifty STL files. [7] Each file was converted into a replica model using either FDM or Polyjet technology. The printed replica teeth were then re-scanned to produce an STL file. A "best fit analysis" of the original STL to each of the subsequent printed model STL files allowed the authors to produce mean deviation measurements. The mean value was 0.047mm for the FDM replicas and 0.038mm for the Polyjet replicas.

Linear and volumetric measurements were also produced which were measured by a single observer. Researchers found that the mean crown width of the FDM replicas were significantly smaller than the extracted teeth at -0.116mm. The mean crown width of the Polyjet group was greater than that of the original group at 0.064mm. The tooth heights were smaller for both groups, but only the FDM group was considered clinically significant. Volumetric measurements for the FDM group showed significantly decreased values, while the Polyjet group showed significantly increased values. The researchers considered the change in volume to be statistically significant for both groups.

ADVANTAGES IN USING ADDITIVE MANUFACTURING

There are several advantages of additive manufacturing technology over that of subtractive manufacturing. Many start-up companies are now producing accurate printing units at a fraction of previous costs thanks to recently expired patents from major distributors. [2] This means that providers will have many more options when it comes time to purchase a machine.

Additive manufacturing is considered a more "passive" means of production. Unlike subtractive manufacturing, there is decreased wear of milling heads and less noise and heat production. [2] There is also a lower percentage of wasted material. "Additive machines tend to mostly use what is required for the build and have 40% less wastage. In addition, around 95% to 98% of the waste may be recycled in future production cycles." [8] Intricate internal features and details can be captured with the 3D printing process, unlike with a milling unit. [9]

For some additive manufacturing techniques such as Fused Deposition Modeling or Selective Laser Sintering, additional steps may be required to place support structures. These would need to be removed following completion of the model. [10]

LIMITATIONS OF ADDITIVE MANUFACTURING

The additive manufacturing process can cause what has been termed a "staircase effect." The final product is built in a series of layers. Even at the smallest resolution, steps can appear on the surface.[11] Each 3D printing method may have its own limitations. The differences in final model dimensions are due material shrinkage that occurs during the building, or in some cases, the postcuring phase.[7] The minimal layer thickness could also limit the accuracy. Although accuracy continues to improve, reproducibility of many additive manufacturing units do not print to the level of accuracy required for certain dental applications.

MATERIALS & METHODS

A full arch master model will be scanned using a laboratory based, white light LED scanner by Degree of Freedom. The Freedom HD scanner utilizes what the company calls the 'Stable Scan Stage' Method for scanning. In this device the camera and light module to rotate around a stable scanning stage. The system uses two 2.0 MP cameras and has a reported accuracy of within 10 microns. The scanned model is viewed via a software program called EXOCAD. The file is saved as an STL file.

The master model's STL file will serve as the "gold standard". From this original STL file, all other models will be fabricated. Three different printers will be used to fabricate 10 models (n=10). The models will be identified and scanned using the same Freedom HD scanner in order to produce an STL file for each of the 30 models. The STL file of each printed model, will be referenced back to the master STL file and deviations measured by 3D metrology using a prescribed error range of ±150 microns. The STL files will be overlaid and a best-fit analysis performed using 3-matic software. The software will be used to provide a graphical and statistical analysis of the findings.

3D Printers

The 3 Dent (EnvisionTec) printer utilizes what the company terms 3SP technology. This stands for scan, spin, and selectively photocure. It employs stereolithography and digital light processing (DLP) technology to build objects layer by layer. The manufacturer claims a build speed of 10mm per hour for the full build envelope. The unit dimensions are 2.42ft x 2.49ft x 3.83ft. The two recommended materials for dental models are E-Denstone 3SP Peach and E-Model Peach 3SP, which are both photopolymers. The maximum build size is 266 mm x 175 mm x 76 mm. This particular unit retails for between $50-100,000.

The Bego Varseo printer utilizes DLP (Digital Light Printing) printing system that uses a variation of stereolithography. The unit dimensions are 110 x 65 x 85 mm. The manufacturer reports a resolution of 60 microns (+/- 30 microns). The Build speed is 20-40 mm/h. The layer thickness is between 50-100 microns. There are multiple materials utilized by the printerto include both wax and resins.

This Projet 5000 Printer utilizes a multi-jet modeling technology. The resolution according to the manufacturer is 750 x 750 x 890 DPI with an accuracy up to 32 microns. Three proprietary build materials are typically used and the technology has the capability to blend multiple materials allowing for greater detail, multiple colors, and various textures.

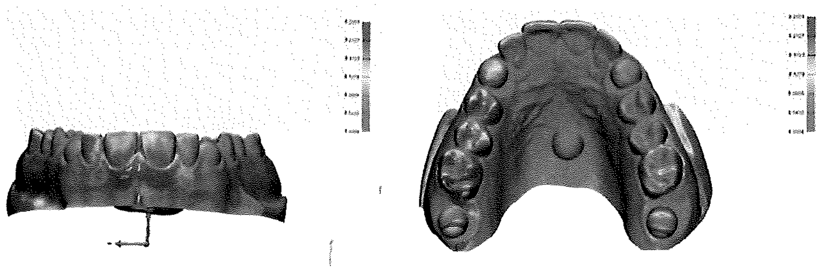
Results

The absolute mean difference for the three printers were as follows: 3Dent produced a mean difference of 79.8 micrometers +/- a standard deviation of 13.0, Bego produced an absolute mean difference of 65.5 micrometers with a standard deviation of +/- 7.8, and Projet 5000 produced an absolute mean difference of 75.5 micrometers with a standard deviation of +/- 23.2. A One-way ANOVA revealed a P value equal to 0.146, therefore no statistically significant difference was found between the three printers.

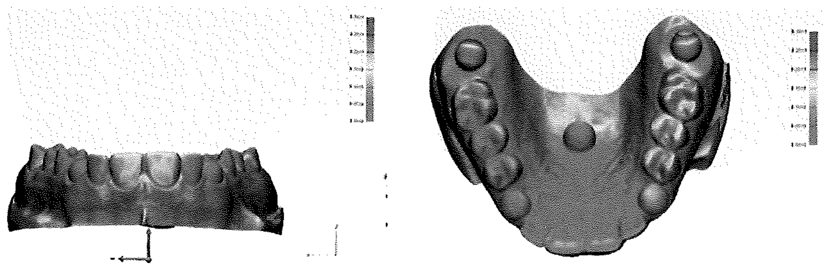
Discussion

The results for all three printers showed an overall mean well within an acceptable range. Often times 100 to 150 microns are quoted as an acceptable amount of error when referring to dental restorations and marginal adaptation. The facial and occlusal images of two of the 3Dent scans, reveal that the vast majority of the model falls within 10 to 50 microns of error. Areas in orange and red are outside of what is considered an acceptable range, reaching upwards of 250 microns of error. Areas in grey are greater than 250 microns. Interestingly, the areas with greater error appear to coincide between the scans.

3Dent Scan 2

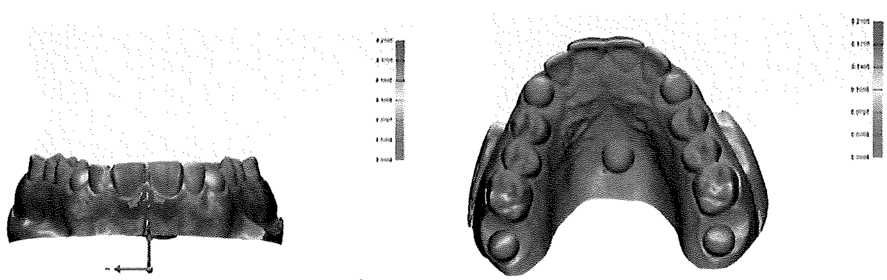


3Dent Scan 4

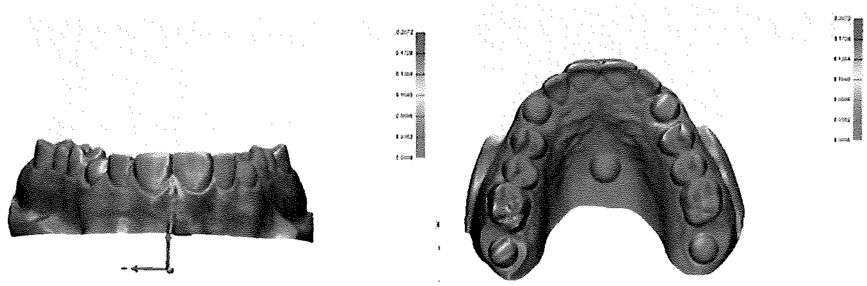


The facial and occlusal views of the Bego scans had common areas of error as well. The vast majority of the models printed using the Bego were well within 100 microns.

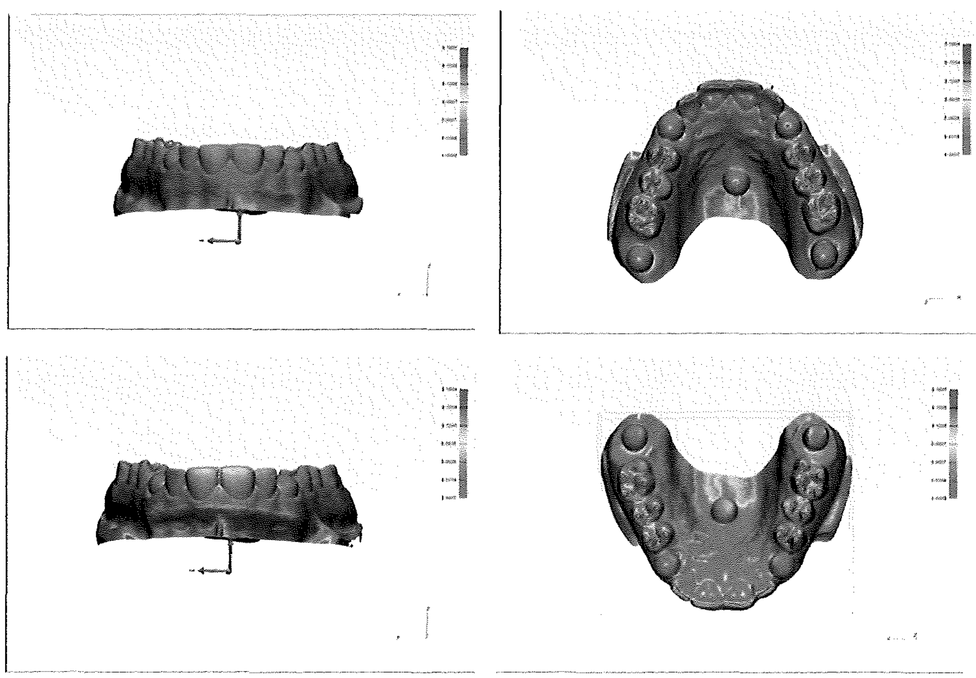
Bego Scan 3



Bego Scan 9



The Projet 5000, based on the manufacturers specifications, would've been a likely choice for having the best accuracy of the three printers. The images from Scan 2 and scan 6 show that there was less accuracy along the cusps and grooves of the teeth. Overall, based on the areas in green, the vast majority was well within an acceptable range.



Projet 5000 Scan 2

Projet 5000 Scan 6

Each printer used in this study used a different method or proprietary process in an attempt to achieve superior accuracy. All three printers achieved an absolute mean difference within an acceptable range, however there were clearly localized areas of each model that fell outside of this acceptable range. The areas of inaccuracy, although localized, would result in unsatisfactory results in the areas of Fixed Prosthodontics. Utilizing 3D printed models for treatment planning, surgical planning or surgical stints remains a valid use for this technology within the field of dentistry.

Conclusion

Overall, the mean values fell within an acceptable range of error, however there were localized areas of the models that fell outside of an acceptable range. Each printer produced inaccuracies in similar areas of the models. The Bego Varseo produced a lower overall mean than both the 3Dent and Projet 5000, however this difference was not clinically significant.

For the purposes of surgical planning or occlusal analysis, the accuracy achieved in this study would be adequate. However, fabricating restorations from a printed model may not be advisable at this time due to the amount of error at certain areas of the model. Follow on studies should consider inter-group comparisons to assess the precision of each printer.

Comparing the results of full arch models to that of single tooth or sextant models could help determine if the build size contributes to areas of inaccuracy. As technology continues to improve, the hope is that in most situations, a 100% digital workflow can be achieved, eliminating the need for a physical impression and stone models. Data analysis for this study are ongoing as well as consideration of follow on studies.

Bibliography

1. Dodziuk, Helena. Applications of 3D printing in healthcare. Kardiochirurgia I Torakochirurgia Polska 2016; 13 (3): 283-293.
2. Barazanchi et al. Additive Technology: Update on Current Materials and Applications in Dentistry. Journal of Prosthodontics 2016; 10.1111/jopr.12510.
3. Wong, K. Hernandez, A. A Review of Additive Manufacturing. Volume 2012, Article ID 208760, 10 pages.
4. K. Cooper, *Rapid Prototyping Technology*, Marcel Dekker, 2001.
5. Kim KB, Kim WC, Kim HY, et al: An evaluation of marginal fit of three-unit fixed dental prostheses fabricated by direct metal laser sintering system. Dent Mater 2013;29:e91-e96.
6. Hazeveld, A., Slater, H., Ren, Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. American Journal of Orthodontics and Dentofacial Orthopedics. January 2014, Vol 45, Issue 1.
7. Lee, Keun- Young et al. Accuracy of three- dimensional printing for manufacturing replica teeth. The Korean Journal of Orthodontics 2015; (45(5):217-225.
8. Berman B: 3-D printing: the new industrial revolution. Business Horizons 2012;55:155-162
9. Abduo J, Lyons K, Bennamoun M: Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. Int J Dent

2014;2014:783948.

10. Liu Q, Leu MC, Schmitt SM: Rapid prototyping in dentistry: technology and application. Int J Advan Manu Tech 2005;29:317-335

11. Masood SH, Rattanawong W, Iovenitti P: A generic algorithm for a best part orientation system for complex parts in rapid prototyping. J Mater Proce Tech 2003;139:110-116

12. Bosch, G. Ender, A. & Mehl, A. A 3-Dimensional Accuracy Analysis of Chairside CAD/ CAM Milling Processes. J Prosthet Dent 2014;112:1425-1431.

13. Silva, D. et al. Dimensional error in selective laser sintering and 3D-printing of models for craniomaxillary anatomy reconstruction. Journal of Cranio-Maxillofacial surgery (2008) 36, 443-449.

14. Joo, Han-Sung et al. Complete- mouth rehabilitation using a 3D printing technique and the CAD/ CAM double scanning method: A clinical report. The Journal of Prosthetic Dentistry (2016) 116, 3-7.

15. Stansbury, J & Idacavage, M. 3D printing with polymers: Challenges among expanding options and opportunities. Dental Materials (2016) 32, 54-64.

16. B. Vaupotic, M. Brezocnik, and J. Balic, "Use of PolyJet technology in manufacture of new product," *Journal of Achievements in Materials and Manufacturing Engineering*, vol. 18, no. 1-2, pp. 319–322, 2006.