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# IMPACT OF THE INTERNAL STRUCTURE DENSITY IN THE PROCESS OF FABRICATION OF ORTHODONTIC MASTER MODELS BY FUSED DEPOSITION MODELING

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## Abstract

*The article focuses on the influence of infill (internal structure of components) in the dimensional accuracy of dental master models during the processes of their fabrication by Fused Deposition Modeling (FDM) technology, and their vacuuming process for production of clear orthodontic aligners. The components, in this case, were the upper jaws (maxillary teeth) of two individual patients (Tzina, Dimitris), which were obtained by intraoral 3D scanning. Patient Tzina at the time of intra-oral scanning was 27 years old and Dimitris was 23 years old. The method of 3D printing was the FDM, and the material used in this research was thermoplastic high impact polystyrene (HIPS). Three different percentages of infill density were set, 60%, 80%, and 100%. For each setting, there were five specimens (thirty 3D printed dental models in total, 15 for Tzina and 15 for Dimitris). After the 3D printing, the models were digitized and measured by GOM ATOS II Triple Scan MV 170 optical 3D scanner and compared with the values of the initial digital models. Then the dental master models underwent the process of Essix-aligners formation (single press) and were rescanned and measured again. The outcome of this research was to examine if the dental master models remain dimensionally accurate after these processes, and which infill provides the optimal and medically approved accuracy.*

## Keywords

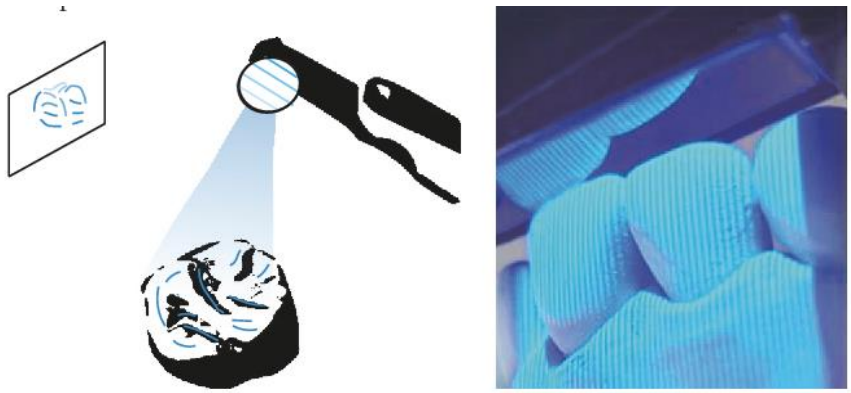
*Master model, FDM, 3D scanning, vacuuming, Essix, comparison, HIPS, infill*

## INTRODUCTION

A significant contribution to the current efficiency in orthodontic practices arises from the digitization of dental models. Such models can be produced nowadays directly and indirectly. The former from a direct scan in the patient's mouth, and the later from scanning of an impression. The digital data collected by the scanning is translated into a 3-Dimensional (3D) model that can be viewed on a 2-Dimensional computer screen. The advantage of this method compared to the conventional one (plaster models) is substantial, it has benefits in efficiency, ease of use, longevity (no risk of physical damage), and storage space [1].

## INTRAORAL SCANNERS

An intraoral 3D scanner is a hand-held device used to directly create a digital impression of the oral cavity. Light source from the 3D scanner is projected onto the scanned objects, such as full dental arches, and then a 3D model processed by the scanning software will be displayed in real-time on a screen. Over the years, computer software and hardware developments have dramatically improved the technologies, completely replacing traditional *polyvinyl siloxane* (PVS) and alginate impressions in a large number of dental and orthodontic offices. New intraoral scanners for acquisition of digital impressions are continuously entering the clinical practice all over the world. Improved technologies have resulted in truly portable systems with a single, forked USB cable that can be plugged into any workstation. Intraoral scanner devices offer numerous applications in orthodontics such as digital storage of study models, advanced software for cast analysis, arch width and length measurements, landmark identification, tooth segmentation, and evaluation of the occlusion [2]. In the experimental research described in the current paper, authors used intraoral iTero scanner and - The iTero Element 2 imaging system with standard resolution. iTero had statistically significant differences based on scanning sequence (ScanR and ScanL) for accuracy of the prepared teeth. ScanL (44 ± 7 μm) showed higher trueness than ScanR (74 ± 4 μm). However, there were no statistically significant differences in precision of prepared teeth between ScanR and ScanL of IOSs.



a) b)

***Fig. 1*** *Schematic representation of intra-oral scanning [3]. a) scheme of digitizing the tooth, b) structured light projected on the tooth*

## 3D PRINTING

The process of 3D printing usually starts with a 3D model, virtually designed or obtained through the scanning process. Slicing software automatically transforms the point cloud into a stereolithographic file (STL file) which is sent to the additive manufacturing machine. Through additive processes, the materials are added in successive layers one above the other to produce every time the desired object [2].

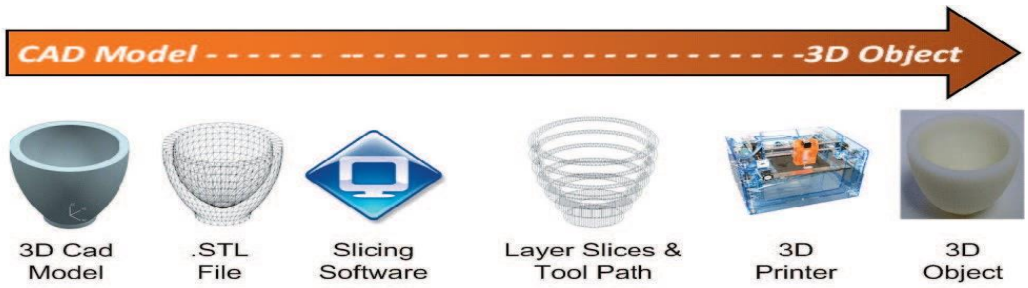



***Fig. 2*** *The 3D Printing process [4]*

## FUSED DEPOSITION MODELING

Fused Deposition Modelling (FDM) is frequently used for modelling, manufacture applications, and prototyping. FDM is based on an additive principle by accumulating materials in layers. The layers of melted plastic instantly combine with each other, thus making very complex parts easily constructed. In order to produce a part, the material is supplied through a heated nozzle after a plastic filament wound in a coil are released. The melted material hardens immediately after extrusion, thus minimizing inaccuracies. The nozzle can be directed in both vertical and horizontal lines by a numerically controlled software mechanism. The materials are deposited in layers and the part is built from the bottom up-one layer at time. In this experimental research, Zortrax M200 3D printer (Fig. 4) was used for manufacturing of the specimens. All printing parameters used in this experimental research are shown in Table 1. Several materials such as Acrylonitrile Butadiene Styrene polymer, polyphenylsulfones and waxes, polycarbonates, among many others, with diverse strength and thermal properties are available [7, 8]. Scheme of the FDM technology is shown in Fig. 3.

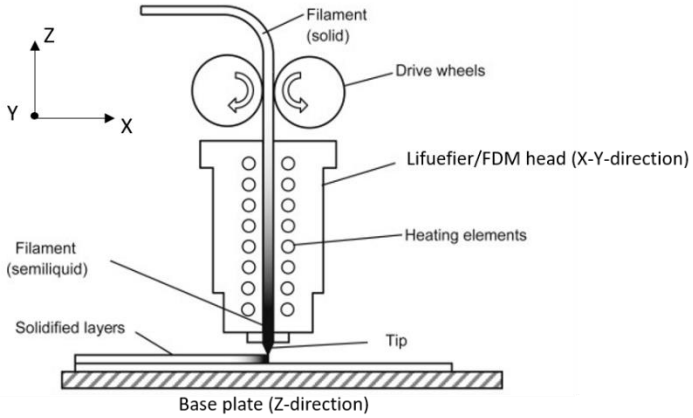



***Fig. 3*** *Scheme of Fused Deposition Modeling [5]*



***Fig. 4*** *Zortrax M200 3D printer used in the experiment [6]*

| **Table 1** Parameters used for additive manufacturing of the samples by Zortrax M200 3D printer | |
|---|---|
| **Parameter** | **Value** |
| Material (-) | HIPS |
| Layer thickness (mm) | 0.09 |
| Infill density (%) | 60, 80, 100 |
| Nozzle diameter (mm) | 0.4 |
| Extrusion temperature (°C) | 230 |
| Platform temperature (°C) | 90 |
| Print quality (-) | high |

## VACUUMING PROCESS

Vacuum process is a manufacturing method used to shape plastic materials. During the vacuum forming process, a sheet of plastics is heated and then pulled around a single print, using suction. Procedure of indirect production of clear aligner with the assistance of vacuuming process is shown in Fig. 5. In this experimental research, one vacuuming for each part took place, totally 30 single vacuuming processes. The vacuuming process is also used in the field of orthodontics for manufacturing Essix-aligners and retainers. These retainers are necessary to ensure that the patient's teeth will not relapse after the orthodontic treatment. Relapse is defined as "the return following correction of features of the original malocclusion." The aim of retention is "to maintain the teeth in their corrected positions at the conclusion of an active orthodontic treatment". This consists of preventive measures, usually achieved with retainers that are either removable, fixed, or a combination of both. Against this background, fractures in removable retainers render them ineffective as the accuracy of their fit against the dentition is compromised, thus relapse can ensue [9, 10, 11, 12].

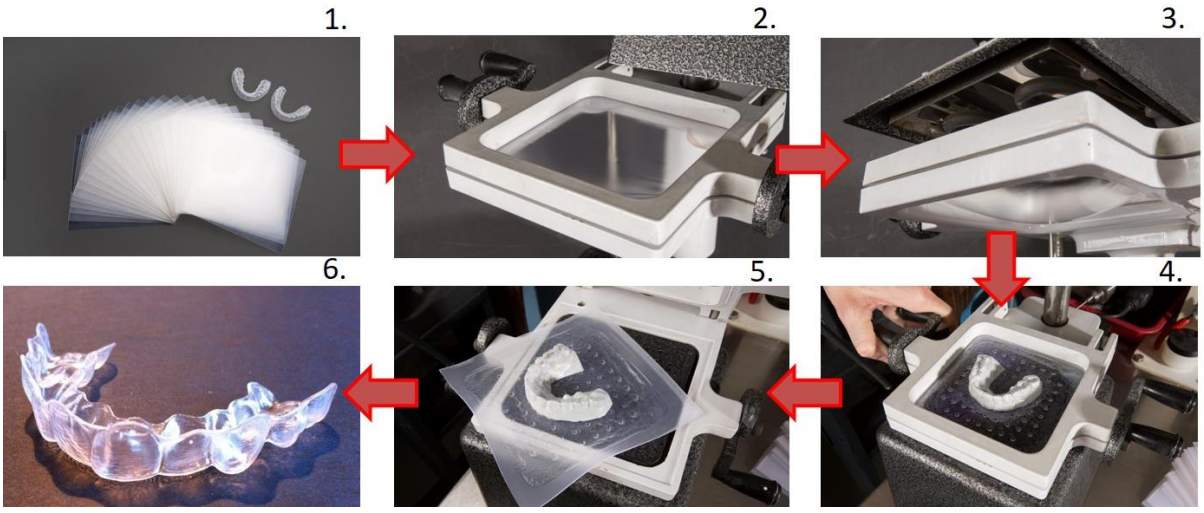



***Fig. 5*** *Procedure of indirect production of clear aligners with the assistance of vacuuming process 1) Transparent foil, 2) fixing the foil to the device, 3) prepared transparent foil, 4) gluing the foil to the model, 5) removing the foil from the device and neckline, 6) final invisible device [13]*

Thermoformed retainers, an increasingly popular type of removable retainers, are made from thermoplastic polymers, with the two principals being semi-crystalline and amorphous [14, 15, 16]. Materials comprising thermoplastic polymers soften when heated above the glass-transition temperature (Tg), as molecular motion forces the polymer chains apart, allowing them to be moulded to a new shape, [17] using either vacuum or pressure–thermoforming techniques. Subsequent cooling below the *Tg*, hardens the material, thus

maintaining the new form. Prior to 1998, orthodontic clear aligner treatment was predominantly for minor tooth movement, usually at the end or orthodontic treatment or to treat minor alignment relapse. In 1998, Align Technology, Inc. introduced Invisalign® to the orthodontic market. It utilized computerized 3D technology to visualize and move the teeth in a virtual model. This technology along with advances in 3D printing and manufacturing efficiencies allowed aligners to be produced in large numbers and in a timely fashion for a variety of clinical cases in the field of Orthodontics: such as deep bite treatment, open bite treatment, space closure, class II and class III malocclusions [18].

## MATERIAL AND METHOD

In this research, authors started with obtaining the intraoral scans of two individuals (Tzina and Dimitris), and they proceeded to their measuring after their visualization in the computer. The measuring was performed between three spots, namely: the (nominal) distance between the most Vestibular point of the 2nd molars (7-7), the 2nd premolars (5-5), and the distance between the cusps of the canines (3-3) as shown in Fig. 7 and Fig. 9. Master models were manufactured by 3D printing using the FDM technology Zortrax M200 3D printer, and the material used was High Impact Polystyrene (HIPS). We printed the dental master models with three different percentages of internal structure: 60 %, 80 % and 100 % (Fig. 6). For each printed dental master model, five specimens were used (30 dental master model in total). After the printing process, the dental master models were digitized and measured again at the same spots as they were measured after the intraoral scan. The printed models of teeth were digitized using the GOM ATOS II Triple Scan optical 3D scanner. The measuring volume (MV) used for the digitization was MV 170 (170 x 130 x 130 mm). The resolution of the cameras was 5 Mpix (the measuring point distance was 0.07059 mm). Process of the 3D scanning is shown in Fig. 8. Parameters which were used for digitizing the models by the GOM ATOS II Triple Scan Optical 3D scanner were as follows: exposure time was set on amount 2; quality was set on "more points", and the resolution was set on "full resolution". The comparison of each scanned model with the reference CAD model and evaluation of the dimensions was made in the GOM Inspect V8 SR1 software [19, 20]. Essix retainers were created to each of our 3D printed dental master models using the vacuum thermoforming technique. Authors proceeded to the separation of the retainers from the dental master models and rescanned the models once again in order to evaluate their response to this process. The aim was to examine if this response was in an extent that is clinically relevant (±0.25 mm). Measuring principle of the tooth is shown in Fig. 9.

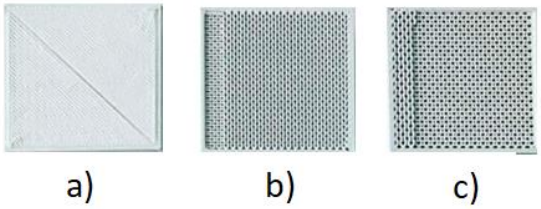



***Fig. 6*** *Schematic representation of density of internal structure: a) 100 %, b) 80 %, c) 60 %*

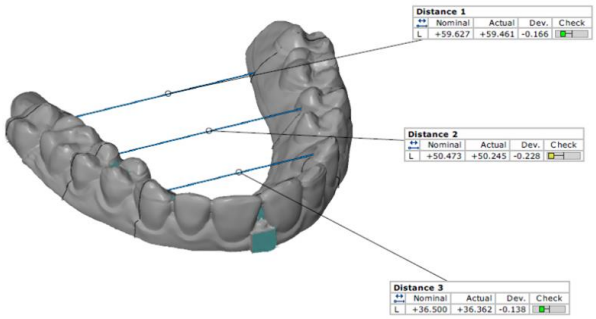



***Fig. 7*** *Distances measured on printed master model*




***Fig. 8*** *Printed master model in the process of 3D digitization*

## HIPS thermoplastic material

High Impact Polystyrene, (HIPS), is a rubber modified version of general-purpose Polystyrene, with the similar properties as ABS thermoplastic material. The addition of rubber makes the thermoplastic incredibly durable, with a much higher impact resistance than its former compound. Like all thermoplastics, the material can become soft and pliable when heated, and re-solidify upon cooling. These factors alone make HIPS a great material to manufacture components with [21]. Properties of the HIPS thermoplastic are shown in Table 2.

**Table 2** Properties of HIPS thermoplastic material

| **Properties** | **Metric unit** |
|---|---|
| Tensile Strength, Yield | 19.3 MPa |
| Elongation at Break | 52 % |
| Tensile Modulus | 1.65 GPa |
| Flexural Yield Strength | 42.7 MPa |
| Density | 1.03 g.mm$^{-3}$ |
| Glass-transition temperature | 100 °C |

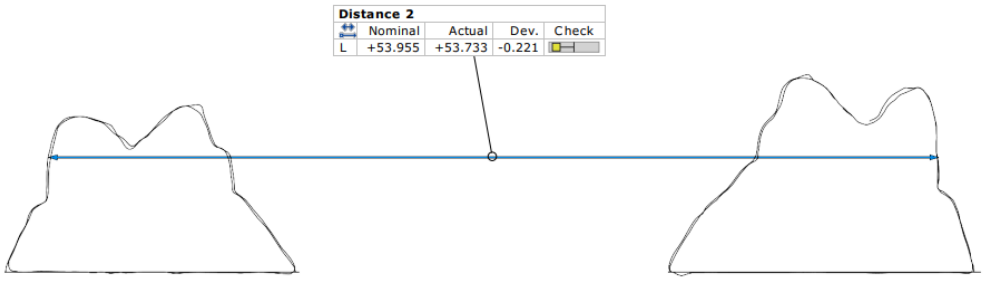



***Fig. 9*** *Measurement principle in the GOM Inspect Software*

## RESULTS

The results are divided into two categories: Pre-vacuuming and Post-vacuuming.

**Table 3** Values for Tzina HIPS 60 % before vacuuming

| Tzina HIPS 60 % (before vacuuming) | | | | | | | |
|---|---|---|---|---|---|---|---|
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.627 | -0.130 | -0.166 | -0.337 | -0.264 | -0.210 | **-0.221** |
| distance 5-5 | 50.473 | -0.189 | -0.228 | -0.340 | -0.262 | -0.234 | **-0.250** |
| distance 3-3 | 36.500 | -0.138 | -0.138 | -0.172 | -0.174 | -0.125 | **-0.149** |

**Table 4** Values for Tzina HIPS 80 % before vacuuming

| Tzina HIPS 80 % (before vacuuming) | | | | | | | |
|---|---|---|---|---|---|---|---|
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.627 | -0.242 | -0.253 | -0.233 | -0.347 | -0.201 | **-0.255** |
| distance 5-5 | 50.473 | -0.208 | -0.269 | -0.311 | -0.358 | -0.280 | **-0.285** |
| distance 3-3 | 36.500 | -0.098 | -0.141 | -0.260 | -0.185 | -0.137 | **-0.164** |

**Table 5** Values for Tzina HIPS 100 % before vacuuming

| Tzina HIPS 100 % (before vacuuming) | | | | | | | |
|---|---|---|---|---|---|---|---|
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.627 | +0.038 | -0.034 | +0.056 | +0.038 | +0.022 | **0.037** |
| distance 5-5 | 50.473 | +0.016 | +0.041 | -0.080 | +0.068 | +0.063 | **0.053** |
| distance 3-3 | 36.500 | +0.182 | +0.138 | +0.104 | +0.097 | +0.149 | **0.134** |

**Table 6** Values for Dimitris HIPS 60 % before vacuuming

| Dimitris HIPS 60 % (before vacuuming) | | | | | | | |
|---|---|---|---|---|---|---|---|
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.249 | -0.261 | -0.165 | -0.136 | -0.167 | **-0.195** |
| distance 5-5 | 53.955 | -0.221 | -0.189 | -0.172 | -0.148 | -0.131 | **-0.172** |
| distance 3-3 | 39.759 | -0.163 | -0.126 | -0.086 | -0.080 | -0.065 | **-0.104** |

**Table 7** Values for Dimitris HIPS 80 % before vacuuming

| Dimitris HIPS 80 % (before vacuuming) | | | | | | | |
|---|---|---|---|---|---|---|---|
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.189 | -0.164 | -0.123 | -0.195 | -0.255 | **-0.185** |
| distance 5-5 | 53.955 | -0.185 | -0.180 | -0.136 | -0.137 | -0.236 | **-0.174** |
| distance 3-3 | 39.759 | -0.024 | -0.058 | -0.007 | -0.026 | -0.169 | **-0.056** |

**Table 8** Values for Dimitris HIPS 100 % before vacuuming

| Dimitris HIPS 100 % (before vacuuming) | | | | | | | |
|---|---|---|---|---|---|---|---|
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.189 | -0.164 | -0.123 | -0.195 | -0.255 | **-0.185** |
| distance 5-5 | 53.955 | -0.185 | -0.180 | -0.136 | -0.137 | -0.236 | **-0.174** |
| distance 3-3 | 39.759 | -0.024 | -0.058 | -0.007 | -0.026 | -0.169 | **-0.056** |

| **Table 9** Values for Tzina HIPS 60 % after vacuuming | | | | | | | |
|---|---|---|---|---|---|---|---|
| Tzina HIPS 60 % (after vacuuming) | | | | | | | |
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.293 | -0.367 | -0.407 | -0.287 | -0.261 | **-0.264** |
| distance 5-5 | 53.955 | -0.321 | -0.367 | -0.411 | -0.335 | -0.301 | **-0.347** |
| distance 3-3 | 39.759 | -0.187 | -0.218 | -0.226 | -0.169 | -0.157 | **-0.191** |

| **Table 10** Values for Tzina HIPS 80 % after vacuuming | | | | | | | |
|---|---|---|---|---|---|---|---|
| Tzina HIPS 80 % (after vacuuming) | | | | | | | |
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.343 | -0.330 | -0.277 | -0.287 | -0.180 | **-0.283** |
| distance 5-5 | 53.955 | -0.267 | -0.326 | -0.354 | -0.310 | -0.419 | **-0.335** |
| distance 3-3 | 39.759 | -0.128 | -0.168 | -0.253 | -0.153 | -0.232 | **-0.186** |

| **Table 11** Values for Tzina HIPS 100 % after vacuuming | | | | | | | |
|---|---|---|---|---|---|---|---|
| Tzina HIPS 100 % (after vacuuming) | | | | | | | |
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.103 | -0.151 | -0.063 | -0.124 | -0.140 | **-0.116** |
| distance 5-5 | 53.955 | -0.094 | -0.060 | -0.154 | -0.020 | -0.030 | **-0.071** |
| distance 3-3 | 39.759 | +0.150 | +0.083 | +0.082 | +0.067 | +0.104 | **0.097** |

| **Table 12** Values for Dimitris HIPS 60 % after vacuuming | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dimitris HIPS 60 % (after vacuuming) | | | | | | | |
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.298 | -0.271 | -0.368 | -0.093 | -0.359 | **-0.277** |
| distance 5-5 | 53.955 | -0.264 | -0.250 | -0.286 | -0.266 | -0.343 | **-0.281** |
| distance 3-3 | 39.759 | -0.169 | -0.144 | -0.213 | -0.209 | -0.255 | **-0.198** |

| **Table 13** Values for Dimitris HIPS 80 % after vacuuming | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dimitris HIPS 80 % (after vacuuming) | | | | | | | |
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.245 | -0.075 | -0.289 | -0.288 | -0.309 | **-0.241** |
| distance 5-5 | 53.955 | -0.219 | -0.302 | -0.242 | -0.242 | -0.265 | **-0.254** |
| distance 3-3 | 39.759 | -0.104 | -0.138 | -0.190 | -0.110 | -0.159 | **-0.140** |

| **Table 14** Values for Dimitris HIPS 100 % after vacuuming | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dimitris HIPS 100 % (after vacuuming) | | | | | | | |
| - | Nominal [mm] | Print 1 [mm] | Print 2 [mm] | Print 3 [mm] | Print 4 [mm] | Print 5 [mm] | Arithmetical mean [mm] |
| distance 7-7 | 59.918 | -0.066 | -0.218 | -0.076 | -0.116 | -0.021 | **-0.099** |
| distance 5-5 | 53.955 | +0.047 | +0.089 | +0.029 | -0.019 | +0.080 | **0.052** |
| distance 3-3 | 39.759 | +0.073 | +0.170 | +0.072 | +0.040 | -0.017 | **0.074** |

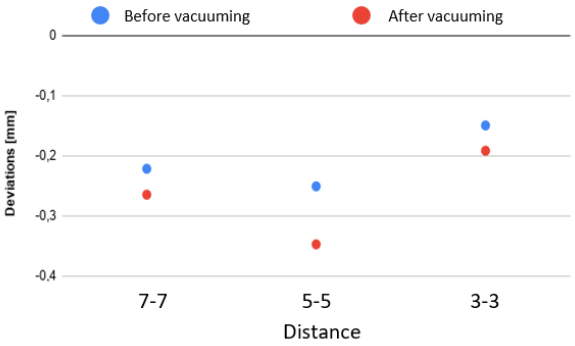



***Fig. 10*** *Graph: deviations – distance. Tzina 60 % before and after vacuuming*

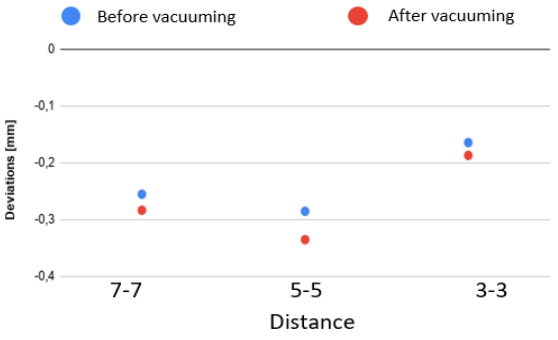



***Fig. 11*** *Graph: deviations – distance. Tzina 80 % before and after vacuuming*

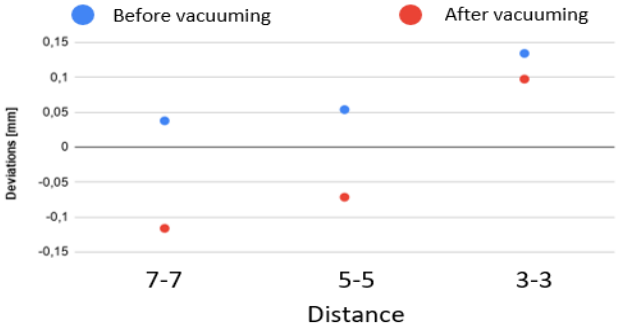



***Fig. 12*** *Graph: deviations – distance. Tzina 100 % before and after vacuuming*

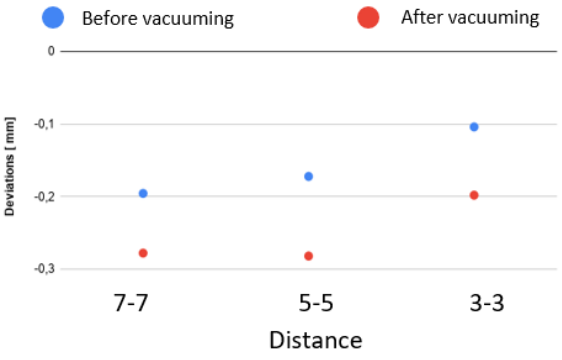



***Fig. 13*** *Graph: deviations – distance. Dimitris 60 % before and after vacuuming*

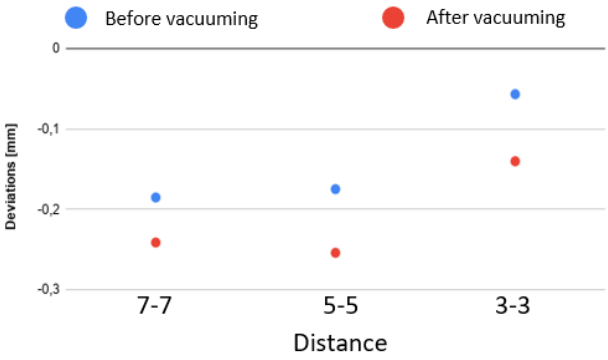



***Fig. 14*** *Graph: deviations – distance. Dimitris 80 % before and after vacuuming*

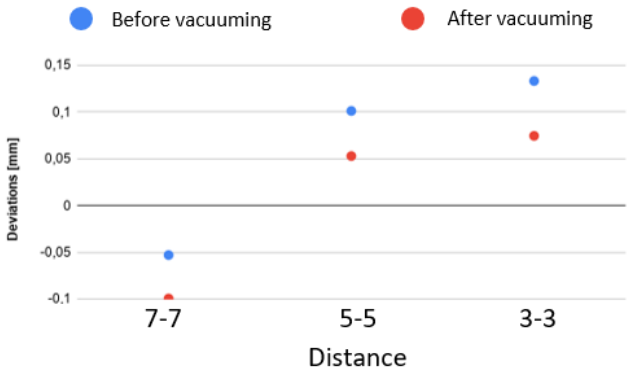



***Fig. 15*** *Graph: deviations – distance. Dimitris 100 % before and after vacuuming*

## CONCLUSION

The tables and graphs suggest that, at the end of the processes of 3D printing and vacuuming-thermoforming, there is a decrease in the nominal distance of the intraoral scans. The noticeable shrinkage which occurred can be attributed to the properties of the material (HIPS), the increased temperature which occurred during the process of vacuum-thermoforming, and to the different internal structures (infill) of each dental master model. The shrinkage of plastics signifies the volume contraction of polymers during the cooling step of their processing (3D printing). This contraction is partly due to the difference in density of polymers between the melt state and the cooled rigid state. The shrinkage occurs after ejection as the part continues to cool and after that, the part may continue to shrink very slightly until the temperature and moisture content stabilizes [22]. Another important factor that influences the degree of the occurring shrinkage is the internal structure of our 3D printed casts (infill). When building a cast, it is very common to use a range of infill patterns and densities with the aim of reducing printing time and consuming the least material needed. Infill densities can vary, so the infill pattern can be either line, rectilinear, or honeycomb (in our experiment was a linear pattern of infill). In our experiment, we noticed that in all cases (Tzina's and Dimitris upper jaw with 3 different infills) shrinkage occurred, however, in the models with 100 %, the shrinkage is the smallest, staying within the tolerance of permissible values ± 0.25 mm. Therefore, by using 100 % percent for the infill of our models, we achieved the most accurate model regarding its dimensional stability with the smallest deviation from the patient's mouth.

We mentioned the importance of the aligners in the prevention of relapse, in space closing, and in many other clinical cases; therefore an aligner that is not deformed at the end of the process of its production is crucial for its efficacy and reliability.

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