

Accuracy of orthodontic movements with 3D printed aligners: A prospective observational pilot study

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Objective: Owing to the availability of 3D software, scanners, and printers, clinicians are encouraged to produce in-office aligners. Recently, a new direct-printing resin (Tera Harz TC-85DAC) has been introduced. Studies on its mechanical characteristics and biological effects have been published; however, evidence on its efficacy in orthodontic treatment remains scarce. This pilot study aimed to investigate the accuracy of teeth movement achieved with direct-printed aligners. **Methods:** Seventeen patients (eight males and nine females) with a mean age of 27.67 ± 8.95 years, presenting with dental rotations $< 30^\circ$ and spaces/crowding < 5 mm, were recruited for this study. The teeth movement was planned starting from a T0 digital dental cast. The 3D direct-printed aligners were produced using Tera Harz TC-85DAC resin. Once the orthodontic treatment was completed, a final digital cast was obtained (T1). The planned teeth positions were then superimposed onto the T0 and T1 digital models. The differences between the programmed movements and the achieved overall torque, tip, rotation, and transverse dimensions were assessed using the paired *t* test or Wilcoxon's signed rank test. **Results:** The overall accuracies for torque, tip, and rotation were 67.6%, 64.2%, and 72.0%, respectively. The accuracy of the change in transverse diameter was 99.6%. **Conclusions:** Within the limits of the present pilot study (difficulties with abnormally shaped teeth and use of attachments), it can be concluded that 3D printed aligners can be successfully printed in-house and utilized for mildly crowded cases, with a comparable accuracy of tooth movement to that of other aligners.

Key words: Resin, Tooth movement, 3D printed aligners, In office aligners

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INTRODUCTION

Therapy with clear aligners has become a part of modern orthodontics since the late 1990s, when clear aligners were first presented to the market as an alternative to the traditional fixed vestibular or lingual braces. This appliance has achieved reliability in orthodontic movements over time.¹ The movement staging protocols have also improved because of the development of auxiliary features, including interproximal enamel reduction (IPR) and refinements when necessary.^{2,3}

The pioneer of this system was Kesling,⁴ who developed a rubber-based tooth positioning appliance in 1945. Since then, the interest in and diffusion of this therapeutic alternative have increased exponentially. Subsequently, a large number of cases can be managed by aligners today.⁵ The esthetic performance and comfort provided by these appliances have increased the number of adult patients seeking orthodontic treatment.⁶

The availability of software that allows in-office set-ups along with 3D scanners, validated 3D printers, and printing materials have encouraged clinicians to produce aligners in-office without the need to communicate with external providers, consequently gaining full control over aligner workflow.⁷ The traditional workflow for in-office aligner production includes a setup for tooth movement and the export of standard triangle language (STL) model files that are 3D printed and then used to produce thermoformed aligners. This type of production has different disadvantages, including production costs that need to be carefully considered, the amount of waste in terms of resin models and plastic used,⁸ and a relatively long postproduction process, including detailing and refining of the final shape of the aligner.

Recently, a new resin for 3D direct printed aligners (DPA) has been introduced.⁶ Its mechanical characteristics have been described as viscoelastic, with peculiar mechanical and physical properties that allow constant and gradual force expression within the limits of physiological tooth movements.^{9,10}

The mechanical properties of the resin differ from those of the standard polyethylene terephthalate glycol (PET-G) and other materials in many aspects, including the shape memory property as well as the lower static force value than that of the traditional PET-G.¹¹ The shape memory characteristic refers to the possibility of the material recovering its original shape at intraoral temperature (37°C) after being bent; approximately 90% of the deformation was reported to be recovered in 10 minutes and 96% in 60 minutes.¹¹

These characteristics are mainly attributed to the molecular composition of the polyurethane polymer cross-linked with methacrylate.¹¹

The biological effects of the resin on human fibroblasts and cytotoxicity have also been investigated, concluding that there are no cytotoxic activities or estrogenic effects. Additionally, the resin does not affect the fibroblast intracellular reactive oxygen species (ROS) levels.¹²

Although the material has been experimentally tested and assessed as reliable for clinical use, studies on its efficacy in orthodontic treatments are lacking.

The aim of this pilot study was to investigate the accuracy of dental movement in consecutively treated patients with limited misalignments using 3D-printed aligners produced with Tera Harz TC-85DAC resin (Graphy, Seoul, Korea). The hypothesis was to verify whether DPA can effectively be used as viable option to solve the above-mentioned cases. The DPA production and orthodontic setup underwent complete in-office management.

MATERIALS AND METHODS

This prospective observational study was approved by the ethics committee (No. 2023/12, University of Genova, Genova, Italy). Written informed consent was obtained from all participants.

The study sample comprised 17 consecutively treated patients (eight males and nine females) with a mean age of 27.67 (standard deviations [SD] = 8.95; the minimum age was 12 years and the maximum age was 56 years).

All the patients involved in this study were treated using in-office-produced aligners prepared by the same operator. All patients were given the same instructions: aligners had to be worn for at least 22 hours per day, except during meals and oral hygiene activities, and were changed every 7 days.

For every patient, a full medical history was collected and full diagnostic records were obtained, along with a thorough clinical evaluation to formulate a correct treatment plan and evaluate whether the case fulfilled the inclusion criteria of the study.

The inclusion criteria included dental rotation of < 30°, diastema or crowding of < 5 mm, and no extraction treatment. The exclusion criteria included systemic pathologies, active or past periodontal disease, previous orthodontic treatment, temporomandibular joint disorders, and ongoing pharmacological treatment that could influence orthodontic treatment.

One patient was excluded from the study because he did not follow the instructions; wearing the aligner by wearing it for only 12–15 hours per day.

Virtual setup

Virtual treatment setup was completed using the aligner module in OnyxCeph® (Onyxceph, Chemnitz,

Germany) software. Teeth positions were planned according to esthetic and functional principles, starting with the 3D T0 digital model and aligning and leveling dental arches following orthodontic aligner biomechanical principles. Each aligner had a planned movement speed of 0.2 mm linear displacement, 2° long-axis rotation, and a vestibulo-lingual inclination of 2.5°.

No auxiliaries, such as temporary anchorage devices or sectional vestibular appliances, were used during treatment, whereas attachments, power ridges, gingival margin design, bite ramps, elastics, or IPR were used and edited when necessary. Rectangular attachments were used on only seven teeth (maxillary incisors, one maxillary and one mandibular premolar, and one maxillary canine).

After the first set of aligners, additional refinement aligners were produced when required to accomplish all treatment goals.

Aligners production

In-office aligners were 3D printed using instructions provided by the manufacturer and described more precisely later. The aligners were printed using a Phrozen Sonic XL 4k 2022 3D printer (Phrozen Technology, Hsinchu, Taiwan) and Tera Harz TC-85DAC resin (Graphy). Aligners were designed with a 0.5 mm thickness, and a 0.05 mm offset was set between the aligner and the model. The aligners were printed in successive 100 µm layers. The supports were manually designed and planned using Uniz software (Uniz, San Diego, CA, USA) to ensure the correct position and angulation of 60° on the printer plate, according to the manufacturer's instructions (Figure 1). The supports were planned on the lingual and occlusal surfaces of the aligners. When the printing process ended, the aligners were removed from the printer plate, and the supports were manually removed from the aligners.

After printing, an excess resin removal step is recom-

mended by the manufacturer. Once the aligners are removed from the printer plate, the excess resin inside the aligners can be observed; this excess has to be removed from the aligners' inner surface using a centrifuge that spins at 1,000 revolutions per minute.

The aligners were positioned such that their inner parts faced outwards; thus, the centrifugal force acted on the excess resin that was removed. This procedure required six minutes to complete.

Subsequently, the aligners were postcured for 14 minutes in a postcuring unit (Tera Harz Cure; Graphy) with a nitrogen generator.

After curing, the aligners were washed in hot water (80°C) for 60 seconds and then checked for surface irregularities. If needed, a polishing disc was used to refine and smooth the aligners (List B; Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany). The procedure was terminated by allowing the aligners to dry for 1 hour at room temperature.

Digital measurements

Pre- and posttreatment digital casts were acquired using a Trios intraoral scanner (3Shape, Copenhagen, Denmark). The planned models were predicted using software to estimate the treatment results. All models obtained were subsequently exported as STL files.

The superimposition of the last aligner result scan on the corresponding virtual setup was used to obtain the percentage of tooth correction.

STL files were uploaded to the 3D Slicer software (Slicer.org) (BWH, Boston, MA, USA) for digital analysis. All teeth were considered for the measurements.

As described by Huanca et al.,¹³ the occlusal plane was taken on the T0 dental cast as the best-fit plane among the continuation of facial axis of the clinical crown (FACCs) on the gingival palatal limits.

When aligning the T0 cast to the occlusal plane, landmarks at the palatal rugae were used to ensure overlap with the T1 and Tp casts, with the palatal rugae considered stable structures before and after treatment. Points were placed on patient-wise morphologically recognizable spots of the palatal rugae for the T0, T1, and Tp STL files to overlap the casts based on stable structures.¹⁴

Models were compared using trigonometry, placing six points for each tooth according to the disposition described by Huanca et al.¹³ and well resumed by Santos et al.¹⁵

- Mesial point of the occlusal surface (MO)
- Distal point of the occlusal surface (DO)
- Gingival limit of the FACCs buccal axis (GL)
- Occlusal limit of the FACCs buccal axis (OL)
- Gingival limit of the lingual FACCs (continuation of the buccal FACC axis on the lingual face) (GLL)

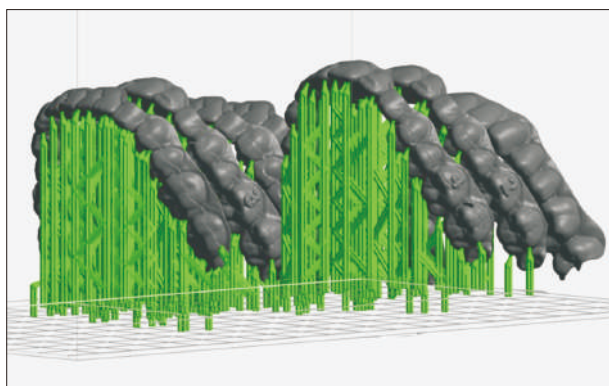


Figure 1. Supports using Uniz software.

- Centroid of teeth (CT): The midpoint of a line passing from the gingival limit of the FACC buccal axis (GL) to the occlusal limit of the FACC buccal axis (OL)

Angular measurements of vestibulo-lingual tipping, mesio-distal tipping, and rotation, as well as the linear measurements of vertical displacement and transversal dimension, were performed on the three digital casts that had been previously superimposed (Figure 2A and 2B).

The rotation angles were measured using the mesiodistal axis (the line passing from the MO to the DO points) with respect to the medial plane (Figure 2D).

The inclination and angulation angles were calculated using the FACC axis (the line passing from the GL point to the OL point) and compared with the T0 occlusal plane (Figure 2F).

The transverse dimension was calculated for three points for every first molar, first and second premolars, and canine, taking the distance between the GL, GLL, and CT points for every above-mentioned tooth and its counter-lateral (Figure 2E).

For the posterior teeth, from the canines to the first molar, when projected, linear measurements of the transverse dimension were taken according to the measurements described by Huanca et al.¹³ Additionally, three points were taken for these teeth to calculate the buccal, lingual, and centroid transverse dimensions.

The superimposition allowed the observation of the differences between the initial, final, and planned dental positions in the three different models.

The occlusal plane at T0 was used as a reference and

described as a stable plane during malocclusion modification (Figure 2C).

A subset of 20 tip, torque, and rotation measurements were repeated. The repeatability of the torque, tip, and rotation measurements was evaluated using the intra-class correlation (ICC) coefficient. The ICC coefficients for torque, tip, and rotations were 0.95, 0.95, and 0.96, respectively.

The accuracy was calculated to investigate the amount of movement actually achieved compared to the planned movement. Every tooth, torque, tip, and rotational movement was calculated as follows:¹

$$[(\text{PositionT1} - \text{PositionT0} / \text{PositionTp} - \text{PositionT0})] \times 100$$
 where Tp is the programmed STL file.

For transverse dimension changes, it was calculated as follows:

$$[(\text{Transverse DimensionT1} / \text{Transverse DimensionTp})] \times 100$$

Whenever the accuracy exceeded 100% (as occurred in a limited subset of samples; for instance, when the vestibularization obtained in the lower anterior region was greater than that in the predicted one), the excess was subtracted and 100% was indicated, meaning that the planned movement had been fully achieved. The accuracy was calculated for teeth that were planned to undergo pure movement only (torque change, tip, and rotation). Teeth temporarily involved in lingual/vestibular or mesiodistal corporal movements were excluded. The teeth showing a planned or obtained movement

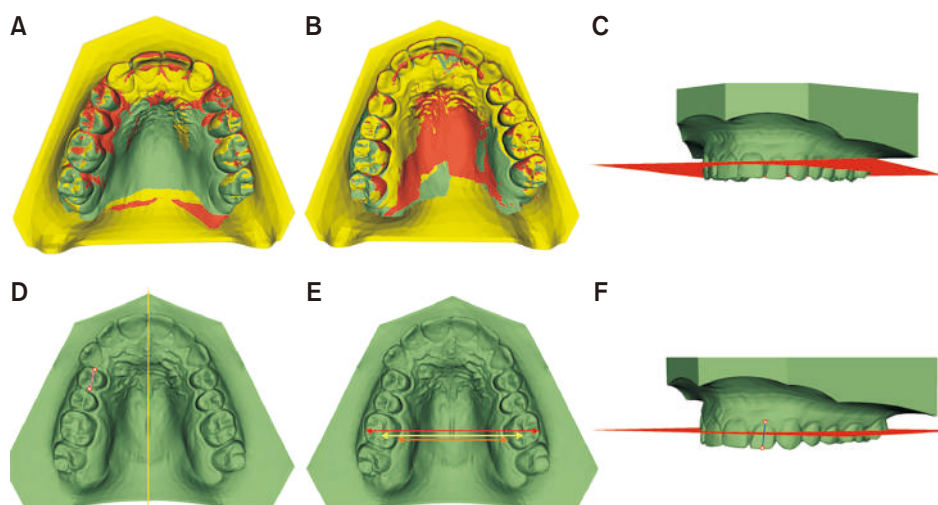


Figure 2. A, B, Superimpositions example of the three standard triangle language files. T0 dental cast (green) and T1 dental cast represents teeth in the real final position (red). The Tp dental cast (yellow) represents the planned final position of the teeth. C, T0 dental cast oriented on the occlusal plane. D, Rotation is calculated as the mesiodistal axis (of the first premolar) with respect to the median plane. E, Transverse dimensions calculated at three different levels. F, The FACC axis (of lateral incisors). Inclination and angulation values were calculated with respect to the occlusal plane.

lower than a threshold of 0.5° for the tip and torque or 1.5° for rotations were excluded according to the mean error analysis resulting from the intraobserver agreement test of measures. It was noticed that under those values, it was not possible to replicate the operator evaluation. Accepting values lower than these thresholds would lead to anomalies in the computation accuracy.

Error analysis

The ICC analysis was performed to evaluate the accuracy and precision of the measurements, and the ICC values for the tip, torque, and rotation were 0.94, 0.91, and 0.95, respectively.

Statistical analysis

The normality of data, the Shapiro–Wilk test was used to verify data normality. Continuous variables are given as the means $\pm$ SD or medians with an interquartile range (whenever not normally distributed), whereas categorical variables were given as a number and/or percentage. The accuracy was described as a percentage.

The differences between the overall torque, tip, and rotation achieved, and programmed movements were tested using the paired *t* test (in the case of normal distribution) or Wilcoxon's signed rank test (if normality

failed), adjusted using the Bonferroni method. As normally distributed, the differences between the achieved and programmed transverse dimensions were tested using the paired *t* test. The differences were considered statistically significant at $P < 0.05$. Data were acquired and analyzed in the R v4.2.2 software environment (R Foundation, Vienna, Austria).

RESULTS

The torque, tip, and rotation changes in 30, 41, and 66 teeth, respectively, and the transverse dimensions of all patients at the described landmark points were analyzed. The accuracy percentages sorted according to movement and tooth are listed in Table 1. The overall accuracy of the torque was 67.6%, ranging from 41.2% for the first maxillary premolars to 100.0% for the mandibular central incisors. The overall accuracy of the tip was 64.2%, ranging from 17.6% for the second maxillary premolars to 100.0% for the maxillary central incisors. The overall accuracy for rotations was 72.0%, ranging from 53.6% for the mandibular canines to 98.0% for the maxillary first premolars. The overall accuracy for the transverse diameter changes was 99.6%, with separate values showing low variability among the different

Table 1. Mean (or median) accuracy rate for the teeth and movement

	Torque (n = 30)	Tip (n = 41)	Rotation (n = 66)	Transverse dimension
Teeth				
Maxillary central incisors	53.0	100.0	84.9	NA
Maxillary lateral incisors	68.0	66.3	59.6	NA
Maxillary canines	65.0	62.4	55.4	100.0
1st maxillary premolars	41.2	-	98.0	100.0
2nd maxillary premolars	56.3	17.6	73.8	100.0
1st maxillary molars	-	-	62.5	100.0
2nd maxillary molars	-	-	-	NA
Mandibular central incisors	100.0	53.5	70.3	NA
Mandibular lateral incisors	83.5	86.5	65.0	NA
Mandibular canines	74.9	87.9	53.6	98.6
1st mandibular premolars	57.6	38.2	86.8	98.5
2nd mandibular premolars	57.5	41.1	81.7	99.4
1st mandibular molars	-	-	-	99.9
2nd mandibular molars	-	-	-	NA
Overall	67.6	64.2	72.0	99.6
<i>P</i> value*	0.495	0.673	0.582	0.939

NA, not assessed; -, sample not suitable for appropriate evaluation.

*Paired *t* test, or Wilcoxon signed rank test, *P* value for the difference between the planned and achieved movement (cumulative comparison for every type of movement).

measured distances.

No statistically significant differences were found between the planned and actual overall torque, tip, and rotation movements ($P = 0.495$, 0.673 , and 0.582 , respectively).

For every landmark point and tooth, no significant differences were found between the achieved transverse diameters and the corresponding programmed changes (Table 2).

In Tables 3–5, the programmed movement, achieved movement, and lack of correction for tooth type are reported using the approach described by Castroflorio et al.¹⁶

The time required to produce eight aligners was measured once the printer had completed the process for both 3D-printed and in-office thermoformed aligners.

The entire workflow includes the import of intraoral

scans, teeth segmentation and setup, and the serial export of all aligners or model files to be printed. Considering the eight aligners (Phrozen Sonic XL 4k build plate limit), approximately 35 and 100 minutes were necessary for 3D-printed and thermoformed aligners, respectively, to be completely produced and ready to be delivered to the patients. These values can change by considering the use of different types of equipment.

Every patient reached crowding resolution after 7.2 aligners on average for the misaligned arch. Six patients did not require any refinement, while nine and two patients required one and two refinements, respectively, using new scans. All patients received a fixed retainer after orthodontic treatment.

Table 2. Programmed and achieved inter-teeth distance

	Torque	Programmed distance (n = 16 patients)	Obtained distance (n = 16 patients)	P value*
Transverse dimension (mm)				
1st maxillary molars	Buccal	55.78 ± 3.48	55.92 ± 3.52	0.926
	Lingual	35.91 ± 2.86	35.96 ± 2.79	0.966
	Centroid	46.79 ± 3.07	46.52 ± 2.95	0.835
2nd maxillary premolars	Buccal	49.45 ± 3.01	49.55 ± 3.18	0.938
	Lingual	32.54 ± 2.57	32.57 ± 2.71	0.974
	Centroid	41.00 ± 2.52	41.06 ± 2.61	0.952
1st maxillary premolars	Buccal	43.86 ± 2.87	44.00 ± 2.92	0.903
	Lingual	28.25 ± 2.26	28.03 ± 2.40	0.813
	Centroid	35.86 ± 2.30	36.03 ± 2.26	0.845
Maxillary canines	Buccal	35.57 ± 3.99	36.04 ± 3.88	0.769
	Lingual	24.05 ± 2.75	24.11 ± 2.53	0.956
	Centroid	35.57 ± 3.99	36.04 ± 3.88	0.998
Mandibular canines	Buccal	29.10 ± 2.03	28.90 ± 2.29	0.857
	Lingual	19.70 ± 1.55	19.30 ± 1.51	0.613
	Centroid	24.25 ± 1.21	23.93 ± 1.57	0.655
1st mandibular premolars	Buccal	38.49 ± 1.88	38.30 ± 2.16	0.854
	Lingual	26.23 ± 2.23	25.86 ± 2.39	0.752
	Centroid	31.69 ± 3.00	30.87 ± 2.38	0.554
2nd mandibular premolars	Buccal	44.93 ± 2.06	44.82 ± 2.14	0.923
	Lingual	30.70 ± 3.26	30.37 ± 3.49	0.848
	Centroid	36.21 ± 3.18	36.07 ± 3.20	0.929
1st mandibular molars	Buccal	52.55 ± 3.36	52.69 ± 3.35	0.947
	Lingual	34.78 ± 3.57	34.73 ± 3.75	0.975
	Centroid	42.93 ± 3.71	42.89 ± 3.63	0.984

Values are presented as mean ± standard deviation.

*Paired *t* test *P* value.

Table 3. Tip programmed movement, achieved movement, and lack of correction for tooth

Tooth	Tip (n = 41)		
	Prescribed movement (°)	Achieved movement (°)	Lack of correction* (°)
Maxillary central incisors	-1.59 (-3.15, 0.57)	-1.12 (-2.33, 0.62)	0.22 (0.00, 0.78)
Maxillary lateral incisors	1.17 (-0.04, 2.51)	0.84 (-0.25, 1.89)	0.16 (0.00, 0.49)
Maxillary canines	-3.18 (-3.18, -3.18)	-2.42 (-2.42, -2.42)	0.76 (0.76, 0.76)
1st maxillary premolars	-	-	-
2nd maxillary premolars	-	-	-
1st maxillary molars	-	-	-
2nd maxillary molars	-	-	-
Mandibular central incisors	-0.76 (-1.43, 1.02)	0.81 (-0.77, 1.06)	0.00 (0.00, 0.41)
Mandibular lateral incisors	-1.58 (-5.46, 0.59)	-1.22 (-2.86, 0.46)	0.13 (0.00, 0.83)
Mandibular canines	-2.88 (-3.13, -2.07)	-1.61 (-2.38, -1.53)	0.00 (0.00, 0.00)
1st mandibular premolars	3.62 (3.62, 3.62)	1.38 (1.38, 1.38)	2.24 (2.24, 2.24)
2nd mandibular premolars	-2.26 (-2.26, -2.26)	-0.93 (-0.93, -0.93)	1.33 (1.33, 1.33)
1st mandibular molars	-	-	-
2nd mandibular molars	-	-	-

Values are presented as median (interquartile range).

-, sample not suitable for appropriate evaluation.

*Absolute value.

Table 4. Torque programmed movement, achieved movement, and lack of correction for tooth

Tooth	Torque (n = 30)		
	Prescribed movement (°)	Achieved movement (°)	Lack of correction* (°)
Maxillary central incisors	2.47 (1.70, 2.73)	1.04 (0.77, 1.35)	0.22 (0.00, 1.10)
Maxillary lateral incisors	-5.67 (-8.81, -1.77)	-2.14 (-3.64, -0.91)	2.30 (1.06, 3.94)
Maxillary canines	-6.68 (-6.68, -6.68)	-4.34 (-4.34, -4.34)	2.34 (2.34, 2.34)
1st maxillary premolars	-	-	-
2nd maxillary premolars	-6.23 (-6.23, -6.23)	-3.51 (-3.51, -3.51)	2.72 (2.72, 2.72)
1st maxillary molars	-	-	-
2nd maxillary molars	-	-	-
Mandibular central incisors	1.52 (0.67, 1.78)	1.34 (1.09, 1.78)	0.00 (0.00, 0.92)
Mandibular lateral incisors	-1.22 (-5.97, 2.71)	-0.98 (-1.24, 0.50)	0.14 (0.00, 3.96)
Mandibular canines	-0.65 (-4.43, 1.99)	-0.29 (-1.48, 1.12)	0.05 (0.00, 2.63)
1st mandibular premolars	-	-	-
2nd mandibular premolars	2.32 (2.32, 2.32)	1.34 (1.34, 1.34)	0.00 (0.99, 0.99)
1st mandibular molars	-	-	-
2nd mandibular molars	-	-	-

Values are presented as median (interquartile range).

-, sample not suitable for appropriate evaluation.

*Absolute value.

Table 5. Rotation programmed movement, achieved movement, and lack of correction for tooth

Tooth	Rotation (n = 66)		
	Prescribed movement (°)	Achieved movement (°)	Lack of correction* (°)
Maxillary central incisors	-1.98 (-3.05, 2.95)	-1.43 (-2.03, 2.77)	0.28 (0.05, 2.34)
Maxillary lateral incisors	2.46 (-5.48, 4.83)	0.99 (-2.18, 3.29)	0.45 (0.00, 2.00)
Maxillary canines	6.11 (3.32, 8.91)	3.21 (2.27, 5.18)	0.00 (0.00, 1.55)
1st maxillary premolars	-0.41 (-3.27, 2.30)	0.30 (-1.98, 2.61)	0.00 (0.00, 0.00)
2nd maxillary premolars	0.13 (-12.63, 2.51)	-0.20 (-8.77, 1.98)	0.00 (0.00, 1.33)
1st maxillary molars	-	-	-
2nd maxillary molars	-	-	-
Mandibular central incisors	-4.45 (-5.51, -2.54)	-3.00 (-4.24, -2.39)	0.00 (0.00, 0.59)
Mandibular lateral incisors	-4.28 (-8.53, -1.04)	-3.49 (-5.62, -0.56)	1.27 (0.46, 2.89)
Mandibular canines	-4.92 (-7.15, -1.64)	-2.79 (-4.43, -0.61)	0.00 (0.00, 1.05)
1st mandibular premolars	-5.91 (-9.60, -2.21)	-3.69 (-6.32, -1.06)	0.00 (0.00, 0.00)
2nd mandibular premolars	2.42 (2.42, 2.42)	1.98 (1.98, 1.98)	0.00 (0.00, 0.00)
1st mandibular molars	-	-	-
2nd mandibular molars	-	-	-

Values are presented as median (interquartile range).

-, sample not suitable for appropriate evaluation.

*Absolute value.

DISCUSSION

The primary outcome of this pilot study was to determine the accuracy of teeth movement using in-office DPA in treating mildly crowded cases, since these cases can be easily and routinely managed in an office workflow. Low severity cases are indicated when a new material and approach need to be tested. The present pilot study should provide preliminary evidence, considering two aspects: 1) production workflow reliability, including virtual setup, 3D printing, and post-printing process; 2) clinical efficiency.

Viscoelastic properties were previously described experimentally; creep and stress relaxation are typical behaviors for this material, as well as the loss modulus (viscosity) and storage modulus (elasticity). TC-85 showed a storage modulus and loss modulus of 713.6 MPa and 111.60 MPa at 37°C, respectively.¹¹

Considering cytocompatibility, studies showed that during a 14-day *in vitro* test using human gingival fibroblasts, this resin was found to be non-cytotoxic and without estrogenic effects. Additionally, it did not affect intracellular ROS levels.¹² Nevertheless, further research is necessary to verify any long-term effects of using 3D-printed aligners, both *in vitro* and *in vivo*, considering weekly changes in the aligners and the possible release of new material at every step. Accordingly, the correct production procedure, including complete resin polym-

erization, plays a key role in avoiding the risk of material leaching and consequent side effects.¹⁷

Notwithstanding the above, a reaction to the 3D-printed aligner with upper lip swelling was observed in one patient. The reaction was not observed with the initial aligners but with the 4th aligner. This is possibly related to a not properly cured aligner, as after changing the 4th aligner with the following one, the treatment was completed without any other complications. No other adverse events were noticed, and the patients reported good satisfaction, comfort with the aligners, and ease of use.

Movement accuracy

The study of single movements, such as tip, torque, and rotation, does not represent the complex reality of orthodontic treatments and does not include all variables that can potentially impact the final result of an orthodontic movement. This is the premise that all reports on this topic agree on and share when the accuracy of tooth movement needs to be evaluated.¹³ Nevertheless, it is important to understand whether the entire workflow ends in an efficient and acceptable clinical result. Mildly crowded cases could help simplify the analysis because they rarely require complex movements, enabling a proper evaluation of single movements.

The literature on aligner treatment agrees that orthodontic aligners are unable to achieve programmed

movement with 100% predictability, and the results differ with respect to the movement and tooth analyzed.^{18,19}

Rotation

Rotation is generally the poorest movement in terms of accuracy with values as low as 39%.¹⁹⁻²¹ Only one study reported an overall accuracy of 86% for rotation movement,¹ although only 10 patients were evaluated, and the inclusion criteria were similar to those used in the present study. Kravitz et al.²² reported that attachment and IPR have a positive effect on final rotation movement. In the present study, the overall rotation accuracy reached a value of 72%. The greatest value of lack of movement was found for the mandibular incisors. Clinically, these results can be considered good when compared to other studies that planned similar magnitudes of rotation.^{16,19,23} For example, considering maxillary canines, the classic thermoformed aligner therapy showed an accuracy between 58.5% and 62%,¹⁶⁻¹⁹ while the present study showed 55.4% accuracy. However, the accuracy for maxillary central incisors was 61–62% with thermoformed aligners,¹⁶⁻²⁰ and 84.9% with direct-printed aligners.

Tip and torque

The overall tip and torque accuracy values observed were 64.2% and 67.6%, respectively, which can be considered efficient or better than those of the traditional thermoformed aligners. However, this consideration is not generalizable and depends on the tooth movement considered. In fact, Castroflorio et al.¹⁶ described the accuracy of inclination (torque) and angulation (mesial/distal tip) correction for maxillary central incisors as 32% and 22.9%, respectively. Lombardo et al.¹⁹ described higher values (65% and 77%, respectively), whereas in the present study, accuracies of 50% and 100% were achieved. For the maxillary second premolars, accuracies of 56.3% and 17.6% for torque and tip movement, respectively, were found in the present study, compared to less than 10% and 19.9% for thermoformed aligners in one study,¹⁶ and between 70% and 71% in another study.¹⁹

Transversal movement

Transversal dimension values were particularly high, but we should advise that only small expansion movements were necessary to help solve crowding. Further studies are necessary to investigate larger expansion movements. Nevertheless, for the rotation movements, the accuracy values were significantly higher with 3D-printed aligners than they were with thermoformed aligners, whereas similar values were observed for lingual and labial movements.²⁴

It is necessary to emphasize that the aligners used in the present study were obtained in-office, not as a company service, which could represent an interesting perspective for all orthodontists that actually use an in-office aligner production workflow.

Moreover, it is important to underline some practical aspects. As Zinelis et al.²⁵ described, differences in mechanical properties of 3D-printed orthodontic aligners are dependent on the 3D printer used, so the results of the present study must be considered with respect to the hardware, software, and procedures mentioned above. Any alteration or modification to this procedure could possibly lead to a slightly different result.

Clinical impact

The production of DPA is effective in-office management. Direct printing of aligners represents a promising tool for treating the cases evaluated in the present study, considering the learning curve necessary to obtain a proper result. The opportunities for multiple applications include specific and local force delivery with individual thicknesses, pressure points, and any other function or design that could make orthodontic treatment more efficient. Future studies could help define the standards, limits, and opportunities for this resin.

Limits of the study

Difficulties were observed when measuring teeth with abrasions or those abnormally shaped; placing the occlusal limit of the FACC on their cusps should be performed with extreme precision and accuracy. Regarding the clinical aspect, we need to underline the use of attachments to help with rotation, even though only seven teeth received them. Furthermore, it should be considered that this was a pilot study with a small sample size, but a preliminary report is necessary to guide further studies.

CONCLUSIONS

Within the limits of the present pilot study, it was possible to observe and verify the relevant aspects. The aligners were successfully planned and printed in-office and proved to be effective in treating mildly misaligned cases. Direct printing of aligners represents a promising tool to enhance orthodontic treatment efficiency. Future studies could help define the standards, limits, and opportunities for this resin.

AUTHOR CONTRIBUTIONS

Conceptualization: MM. Data curation: ADM, FFV. Formal analysis: SD. Investigation: MM, TC, GB. Methodology: MM, ADM, AC. Project administration: PP, GG,

MM. Resources: MM. Software: ADM, FFV. Supervision: PP. Validation: GG. Visualization: ADM. Writing—original draft: MM, ADM, FFV. Writing—review & editing: TC, GG.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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