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Accuracy comparison of orthodontic movements obtained with 3D printed and thermoformed aligners: a retrospective cohort study

Marco Migliorati[1*], Marco Posadino[1], Chiara Provenzano[1], Anna De Mari[1] and Sara Drago[1]

Abstract

Aims The aim of this retrospective cohort study is to calculate the accuracy of dental movement in consecutively treated patients treated with thermoformed and direct printed aligners.

Methodology Two patient groups were included in the analysis. The first group consisted of 34 consecutively treated patients (23 females, 11 males; mean age 26.3 ± 13.7 years; age range 9–63), who were treated using 3D-printed aligners and a second group included 40 consecutively treated patients (28 females, 12 males; mean age 27.5 ± 12.5 years; age range 12–57), who received treatment with thermoformed aligners made of polyethylene terephthalate glycol (PETG). Digital analysis were performed to evaluate for every tooth torque, tip and rotational movements for each tooth as well as accuracy of planned movement. (Delta-Dent software, Outside Format, Milano, Italy) as well as accuracy of planned movement. The differences between groups in the toothwise movement accuracy were tested using the Mann-Whitney U test The Kruskall-Wallis test was used to evaluate the difference among teeth values. The differences were considered statistically significant at $P < 0.05$.

Results 1018 teeth were measured. The overall accuracy of the torque was 60% for the DPA group and 66% for the TFA group; was 52% for the DPA group and 61% for the TFA group for the tip and the overall accuracy for rotations was 58% for the DPA group and 69% for the TFA group; none of the differences resulted statistically significant.

Conclusions All treatments were successfully completed with similar amounts of refinement stages. No statistically significant differences were found between the two groups in respect of rotation, tip and torque movements.

Keywords 3D printed aligners, Movement accuracy, In office aligner

*Correspondence:
Marco Migliorati
marco.migliorati@unige.it
[1]Department of Digital Orthodontics and Dentofacial Orthopedics, University of Genoa, Genoa, Italy

Introduction

Since their introduction thermoformed aligners (TFA) have developed significantly allowing nowadays a daily therapeutical option for orthodontic treatments in many malocclusions [1–3].

In most cases, TFA are manufactured by external companies. This involves a digital setup and requires clinical approval. While this outsourced production is beneficial in many clinical situations, it can be costly and lead to long wait times for the patient's aligners to be ready. An alternative is in-office production, where all stages of aligner manufacturing—including the digital setup and 3D printing of the model—can be completed directly in the orthodontist's office. This approach reduces overall production time and can also be more cost-effective. Digital evolution, both in software and hardware, has led to the possibility nowadays to have not only a in-office thermoformed aligner, but also a direct printed aligner (DPA) using a 3D printer instead of the traditional thermoforming method. This evolution potentially allows each clinician, properly equipped to efficiently produce a complete aligner treatment set for their patients. In this context a complete digital workflow includes the use of an intraoral scanner that generate different types of three-dimensional files that can be easily uploaded in an aligner module software. Traditionally those softwares allow the clinician to segment the 3D file, move teeth according to the patients' needs and to export a completed a whole set of models to produce TFA. The introduction of direct printed aligner simplify this step introducing the possibility to export directly the aligner file and use the 3D printer to realize a 3D printed aligner with the proper resin.

3D printed materials has effect both on the production process and in the final aligner characteristics as well. DPA's mechanical characteristics in fact differs from those of TFA aligners; recently introduced the resin for direct aligner production have been reported with specific characteristics such constant light forces and shape memory [4] due to his glass transaction temperature and viscoelastic property. When compared for example for vertical displacement the forces delivered by aligners in the vertical dimension by DPA are more consistent and of lower magnitude than those of TFA aligners as Hertan et al. have showed [5].

Biocompatibility was studied in 14 days exposure in vitro setting and the resin showed no cytotoxicity and estrogenic effect when all the production procedures are carefully used. On the other hand mild cityotocicty was found when not adequate postcuring process have been used for aligner production [6].

Other differences between DPA and TFA aligners include production time, costs, geometry design editing and clinical management.

Since no comparison were published in literature on the clinical efficiency between DPA and TFA, the aim of this research was to evaluate how the material and processing system is able to clinically influence the accuracy of dental torque, tip and rotation movements when TFA and DPA are considered. The null hypothesis was that there is no difference between groups in the accuracy of dental movements.

Both aligner production and orthodontic setup underwent a complete in-office management by the same operator.

Methods

Study design

This was a retrospective cohort study on consecutively treated patients by the same operator. The study received approval from the Ethical Committee (No. 2025/2, University of Genova, Genova, Italy).

Setting

All patients were treated with in-office-manufactured aligners, fabricated and managed by the same operator to ensure consistency. Patients were treated between January 2023 and February 2025. Data collection and analysis ended in April 2025. Treatment protocols were standardized across both groups. Patients were instructed to wear aligners for a minimum of 22 h per day, removing them only for meals and oral hygiene. Each aligner was replaced weekly.

Participants and eligibility criteria

Patients treated with in-office aligners, both with thermoformed and direct printed aligners were included in the study.

A detailed clinical examination was conducted to formulate an appropriate treatment plan and assess eligibility according to the study's inclusion criteria which were the following: dental rotation < 30°, diastema or crowding of < 7 mm, and no extraction treatment. Crowding was assessed using the Digital Analysis 3D Module of the OnyxCeph³™ Software (Image Instruments GmbH, Chemnitz, Germany), a platform for three-dimensional evaluation of dental arch morphology.

Exclusion criteria included the presence of systemic diseases, a history or current diagnosis of periodontal disease, prior orthodontic treatment, single tooth movement treatment, deciduous and missing teeth (excluding the tihird molars), temporomandibular joint disorders, the need for tooth extractions, or any ongoing pharmacological treatment that could potentially interfere with orthodontic outcomes,. Adult patients who received orthodontic and orthopaedic treatment in their growing years as interceptive therapy were included. Treatment protocols were customized for each patient's malocclusion, involving either single or dual-arch therapy. To achieve the desired outcomes, when necessary the protocol incorporated interproximal reduction (IPR) for space management and the placement of composite attachments to ensure the predictability of complex movements like rotations, extrusions, and root torque. If initial objectives were not fully met, refinement stage using adjunctive aligners was delivered. For this study, the analysis was concluded after this first refinement phase, with all subsequent stages excluded from the data.

Exposures, predictors, potential confounders, and effect modifiers

After inclusion and exclusion criteria assessment a total of 74 patients were included in the study: the first group consisted of 34 consecutively treated patients (23 females, 11 males; mean age 26.3 ± 13.7 years; age range 9–63), who were treated using 3D-printed aligners fabricated with Tera Harz TC-85DAC and TA-28 resin (Graphy, Seoul, Korea). The second group included 40 consecutively treated patients (28 females, 12 males; mean age 27.5 ± 12.5 years; age range 12–57), who received treatment with thermoformed aligners made of polyethylene terephthalate glycol (PETG), specifically Erkodur (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany).

Written informed consent was obtained from all participants ($n = 74$) and a comprehensive medical history was recorded. When necessary, at the end of the first set of aligners, additional refinement stages were fabricated to fully achieve the treatment objectives. This study focuses solely on outcomes measured at the end of the first refinement stage; any subsequent treatment stages were excluded from the analysis. Several potential confounders could impact the therapeutic effect and the ultimate accuracy of tooth movement. These included poor patient compliance, appliance breakage, and appliance loss. Furthermore, factors such as age and stress were considered effect modifiers, particularly for influencing compliance and the incidence of bruxism (teeth grinding).

Outcomes

The primary outcome of the study was to evaluate and compare the accuracy of movement obtained at the end of the first aligner series in both groups. The secondary outcome was the comparison of two different resins accuracy in the DPA patient group.

The comparison between measurements at T0 and T1 allowed for the assessment of the actual clinical outcome achieved at the end of treatment. Similarly, the comparison between T1 and Tp highlighted any discrepancies between the achieved and planned results, thereby offering quantitative insight into the accuracy of the tooth movements obtained through orthodontic treatment. For every tooth torque, tip, rotational, mesial/distal and body movements were calculated as follows:

$$\frac{Position T1 - Position T0}{Position Tp - Position T0} \times 100$$

The teeth showing a planned or obtained movement 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.

In some cases accuracy displayed negative values: this happened when the achieved and planned values had discordant values, that is, when one movement seemed to happen in the opposite direction.

Twenty patients were randomly selected and for those tip, torque, and rotation were measured again. The intraclass correlation coefficient was used to assess the interoperator repeatability of the torque, tip, and rotation measurements. Moreover, an intra-observer error assessment by using a Bland - Altman analysis over a sample of 20 measurements of each type (torque, tip, rotation, diameters) was performed.

Virtual setup

Virtual treatment setup was carried out using the aligner module in OnyxCeph³™ software (Image Instruments GmbH). Treatment planning was based on both functional and aesthetic criteria, starting from the 3D digital model at T0. Dental alignment and levelling were executed according to biomechanical principles specific to orthodontic aligner therapy.

Tooth movements were planned with controlled parameters: 0.2 mm of linear displacement, 2° of rotation around the tooth's long axis, and 2.5° of buccolingual inclination per aligner stage. No auxiliary appliances—such as temporary anchorage devices or vestibular segmental appliances—were used. However, attachments, pressure points, gingival margin designs, elastics, and interproximal reduction (IPR) were applied or modified as needed.

Aligners production

In-office aligners were 3D printed according to the manufacturer's specifications, using a Phrozen Sonic XL 4 K 2022 3D printer (Phrozen Technology, Hsinchu, Taiwan) and Tera Harz TC-85DAC and TA-28 resin (Graphy). Aligners were designed with a thickness of 0.5 mm and a 0.05 mm offset between the model and the aligner surface. Printing was performed in 50 μm layers.

Print supports were manually positioned and configured using Uniz software (Uniz, San Diego, CA, USA), ensuring correct angulation at 60° relative to the build platform, as recommended by the manufacturer. Supports were placed on the lingual and occlusal surfaces of the aligners and manually removed after printing.

Excess resin, often present inside the aligners post-printing, was eliminated using a centrifugation process set at 1000 RPM for five minutes, with the aligners oriented so that their inner surfaces faced outward, maximizing resin expulsion through centrifugal force.

Post-curing was conducted with a Tera Harz Cure unit (Graphy) for 14 min under a nitrogen atmosphere, as recommended. The aligners were then immersed in hot water at 80 °C for 60 s and inspected for surface irregularities. When necessary, final finishing was completed using a polishing disc (Lisko-B, Erkodent), and the aligners were air-dried for one hour at room temperature.

Thermoformed aligner workflow

The dental models used for thermoformed aligner fabrication were 3D printed with either the Phrozen Sonic XL 4 K 2022 (Phrozen Technology) or the Anycubic Photon Mono M5s Pro (Shenzhen Anycubic Technology Co., Ltd., Shenzhen, China). Thermoforming was performed using the Erkodent Erkoform-3D Motion device (Erkodent Erich Kopp GmbH) with 0.8 mm Erkodur PETG sheets (Erkodent).

To ensure dimensional accuracy and biocompatibility, all printed models underwent standardized post-processing. Immediately after printing, models were washed in 96% isopropyl alcohol (IPA) using the Form Wash system (Formlabs, Inc., Somerville, MA, USA), which uses mechanical agitation to thoroughly clean all surfaces, including fine anatomical features.

Following the wash, the models were air-dried and post-cured using the Form Cure unit (Formlabs, Inc.), equipped with a 405 nm UV LED system. Post-curing lasted five minutes, as recommended by the resin manufacturer, to complete polymerization and stabilize the models' mechanical properties.

Once thermoformed, aligners were trimmed along the gingival margin using a rotary cutting tool, then polished with a Lisko-B polishing disc (Erkodent) to refine and smooth the edges. Each aligner was carefully inspected for defects, cleaned, and disinfected before delivery. Clinical fit and retention were verified prior to initiating patient use.

Digital analysis

Pre- and post-treatment digital casts were acquired using a Trios intraoral scanner (3Shape, Copenhagen, Denmark). The planned models were created using software to estimate the treatment results. The models obtained at the beginning of treatment, at the end of treatment and of the planned movement, were subsequently exported as standard triangle language (STL) files. STL files were uploaded to the semi-automatic software Delta-Dent (Outside Format, Milano, Italy) for digital analysis. The software received as input the STL files derived from intraoral scans of the patient at T0 (pre-treatment) and T1 (post-treatment). Additionally, an STL file of the virtual setup representing the desired treatment outcome (Tp) was uploaded on the software. On each image, specific reference points were manually identified: the mesial point of the occlusal surface (MO), the distal point of the occlusal surface (DO), the gingival limit of the buccal facial axes of the clinical crowns (FACC) axis (GL), the occlusal limit of the buccal FACC axis (OL), and the gingival limit of the lingual FACC axis—defined as the continuation of the buccal FACC axis on the lingual surface (GLL). The centroids of each tooth were automatically calculated by the software.

To define the reference plane, described as the best-fit plane among the continuation of the facial axis of the clinical crown (FACCs) on the gingival palatal limits, protocols described by Huanca et al. were used. In detail, three anatomical landmarks were selected to define the reference plane: the anterior occlusal plane (superior: OPSA, inferior: OPIA), the anterior midline (superior: LMSA, inferior: LMIA), and the posterior midline (superior: LMSP, inferior: LMIP) (Fig. 1). As output, the software provided values of rotation and angulation for each tooth relative to the defined occlusal reference plane.

Sample size calculation

Thirty-four patients per group achieved 80% power to detect an intergroup difference of 0.20 in the obtained to programmed movement ratio, with an estimated standard deviation in each group of 0.29 and with a significance level (alpha) of 0.05 using a Student's t test.

Sources of bias and comparability between exposure groups

Although the eligibility criteria aimed to mitigate potential bias between the two groups, the clinicians' extensive experience and greater confidence with the TFA system could represent a potential confounding variable. Setup and staging weren't different between the two groups, avoiding differences in the planning and movement quantity.

Statistical analysis

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

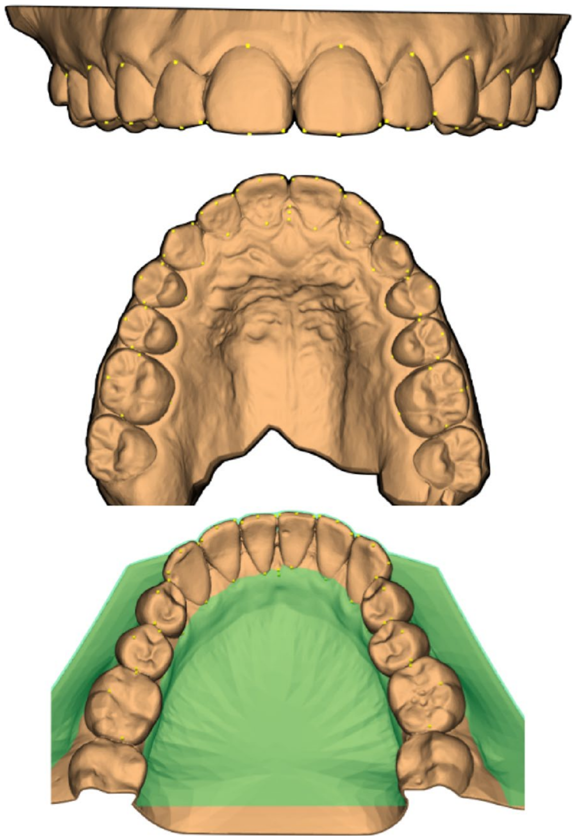

Fig. 1 Points and reference plan used in the study

was described as a percentage. The differences between groups in the overall or toothwise torque, tip, and rotation accuracy were tested using the Mann-Whitney U test adjusted using the Bonferroni method. The Kruskall-Wallis test adjusted using the Bonferroni method was used to evaluate the difference among the tooth values. The Mann-Whitney U test was used again to evaluate the differences between groups according to the type of movement performed. The differences in accuracy among all movement types were assessed by the Kruskall-Wallis test adjusted using the Bonferroni method. The differences between DPA materials in torque, tip, and rotation accuracy were tested using the Mann-Whitney U test adjusted using the Bonferroni method too.

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

Participant flow

Participant flow is reported in the STROBE flow chart. (Fig. 2)

Baseline data

Table 1 reports baseline demographic data.

Numbers analyzed for each outcome, estimation and precision

The intraclass correlation coefficients for torque, tip, and rotations were 0.95, 0.95, and 0.96, respectively.

The Bland-Altman analysis showed the following results: tip mean error: – 0.38°, SD = 1.17, CI [– 1.13, 1.92]; torque mean error: 0.47°, SD = 0.89, CI [– 0.85, 2.21]; rotations mean error: – 1.39, SD = 2.65, CI [– 2.55, 3.81].

According to the aforementioned mean error analysis resulting from the intraobserver agreement test of measures, the teeth showing a planned or obtained movement lower than a threshold of 0.5° for the tip and torque or 1.5° for rotations were excluded. In fact, 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.

In some cases, the accuracy displayed negative values: this happened when the achieved and planned values had discordant values, that is when one movement seemed to happen in the opposite direction.

The measurements of 1018 teeth were considered in the present study. After the selection due to the error thresholds described above, the torque of 722 teeth, the tip of 775 teeth and the rotation of 722 entered the analysis. The accuracy percentages sorted according to group and tooth are listed in Table 2.

Summary of the use of attachment and pressure points are listed in Table 3.

The overall accuracy of the torque was 60% for the DPA group and 66% for the TFA group. This difference was not significant. The overall accuracy of the tip was 52% for the DPA group and 61% for the TFA group; the difference did not result as significant. Finally, the overall accuracy for rotations was 58% for the DPA group and 69% for the TFA group, the difference did not result as significant (Table 2; Figs. 3, 4, 5 and 6). No statistically significant differences were found between the accuracy performance when the two resins where compared (Table 4; Fig. 7).

Initial crowding was 4.6 (SD 1.4) and 4.4 (SD 1.1) for TFA and DPA respectively; difference between groups was not statistically significant.

A total of 2.8 and 2.5 refinement stages were used to complete the whole treatment for DPA and TFA patients respectively. One production (total of 8 aligners) of DPA didn't pass the quality test and wasn't delivered to patient; a new production was used instead.

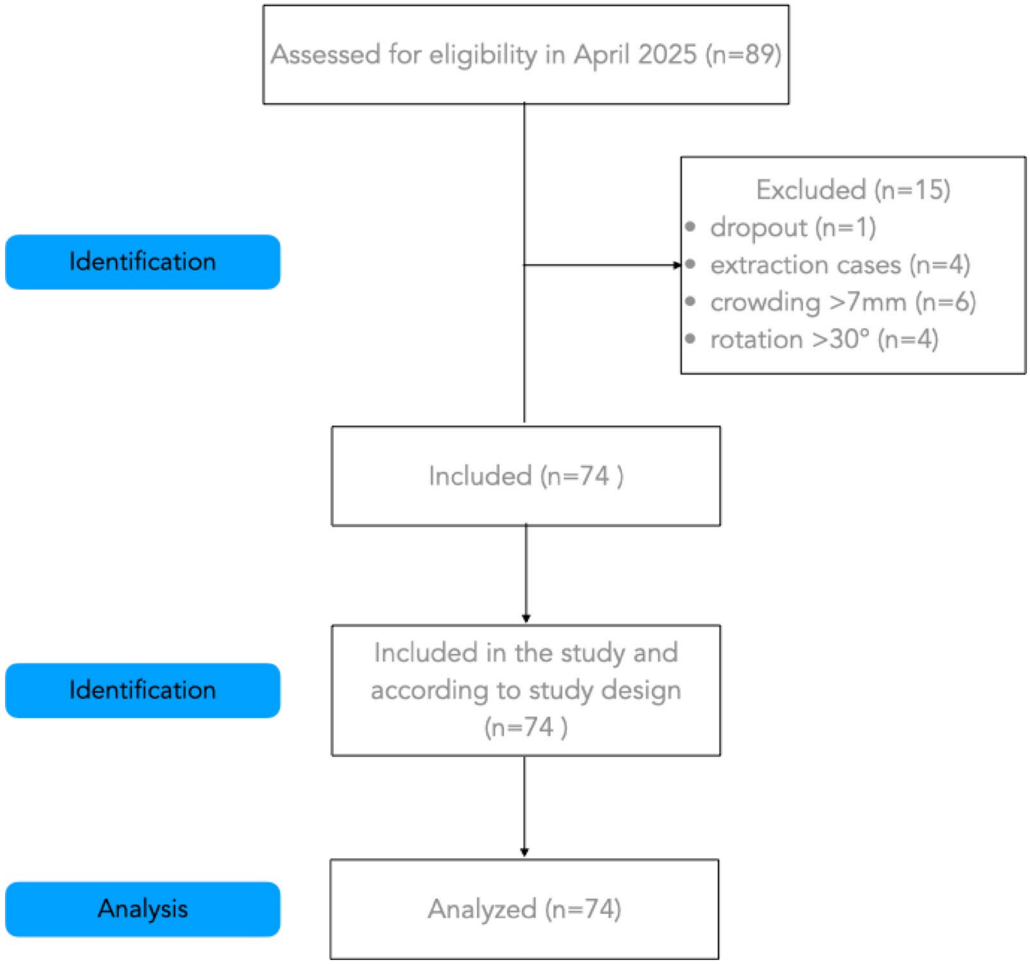

Fig. 2 STROBE study flowchart

Table 1 Demographic baseline data

	Group 1: Tera Harz TC-85DAC/TA-28 resin (Graphy)	Group 2: Polyethylene terephthalate glycol (PETG) Erkodur (Erkodent)
n (total)	34	40
n (females)	23	28
n (males)	11	12
Average age	26.3	27.5
SD (age)	13.7	12.5
Minimum age	9	12
Maximum age	63	57

Discussion

Key results

This study aimed to compare the accuracy of orthodontic movements achieved with direct printed aligners and thermoformed aligners. Baseline patients' characteristics and difficulties were similar, allowing a consistent comparison; To ensure consistency, a single clinician oversaw both the orthodontic setup and the ongoing clinical management of the treatment. Furthermore, the entire production workflow was conducted within the same office Studies on clinical efficiency of direct printed aligners are up to now limited to consecutive cases series or expert reports [7, 8], two main studies have investigated the clinical efficiency and orthodontic movement accuracy using DPA [9, 10] including 17 and 54 patients respectively; the first study was focused on orthodontic accuracy and concluded that 3D printed aligners could successfully be printed in-house and in mildly crowded cases had a comparable accuracy of tooth movement to that of thermoformed aligners. The second study from Knode et al. DPAs found similar results indicating that DPAs may be used to manage mild-moderate malocclusion, producing a significant reduction in PAR score. Both studies reported inflammatory reactions between 3.7 and 5.8% using DPA and both studies attributed this problem to production issues. In the present study on 34 consecutively patients the percentage was 1.9%: 1 patient had a slight reaction (burning sensation and swelling lip) and treatment was completed with thermoformed aligners. Achieving a fully polymerized aligner ready for patient use requires a precise production workflow and

Table 2 Median [interquartile range] of the accuracy rate for tooth and movement

Teeth	Torque			Tip			Rotation		
	Group DPA	Group TFA	*p*-value	Group DPA	Group TFA	*p*-value	Group DPA	Group TFA	*p*-value
Maxillary Central Incisors	61% [17, 104]	70% [36, 121]	0.533	25% [− 137, 95]	51% [− 42, 113]	0.238	50% [24, 94]	60% [4, 116]	0.693
Maxillary Lateral Incisors	16% [− 59, 53]	48% [− 11, 96]	0.151	52% [− 57, 110]	66% [− 40, 109]	0.524	64% [− 38, 112]	57% [− 20, 119]	0.713
Maxillary Canines	66% [22, 102]	73% [− 12, 125]	0.871	42% [− 110, 106]	82% [17, 173]	0.074	40% [− 42, 159]	74% [22, 140]	0.549
I Maxillary Premolars	82% [− 59, 140]	52% [− 100, 109]	0.232	74% [1, 151]	63% [− 29, 108]	0.257	99% [35, 148]	66% [22, 109]	0.151
II Maxillary Premolars	70% [− 29, 100]	45% [− 104, 117]	0.686	68% [− 50, 125]	92% [16, 183]	0.225	40% [− 70, 113]	74% [− 44, 189]	0.289
I Maxillary Molars	81% [15, 143]	77% [5, 153]	0.872	41% [− 88, 158]	70% [− 57, 171]	0.799	96% [25, 167]	54% [− 46, 148]	0.500
Mandibular Central Incisors	93% [20, 175]	80% [15, 108]	0.974	66% [− 39, 160]	38% [− 70, 50]	0.111	70% [38, 86]	60% [9, 230]	0.719
Mandibular Lateral Incisors	39% [1, 94]	100% [18, 153]	0.341	48% [22, 136]	52% [− 78, 176]	0.760	65% [19, 121]	93% [66, 158]	0.181
Mandibular Canines	107% [3, 217]	97% [26, 225]	0.939	120% [− 60, 233]	74% [26, 242]	0.878	37% [18, 95]	64% [− 23, 159]	0.530
I Mandibular Premolars	24% [− 50, 0.93]	76% [− 188, 174]	0.626	16% [− 74, 133]	38% [− 72, 171]	0.723	45% [− 37, 84]	62% [14, 121]	0.500
II Mandibular Premolars	49% [− 42, 109]	94% [− 27, 160]	0.183	40% [− 52, 93]	22% [− 68, 143]	0.922	29% [− 34, 56]	69% [8, 144]	0.101
I Mandibular Molars	53% [1, 150]	56% [− 50, 126]	0.681	18% [− 123, 88]	32% [− 37, 133]	0.331	60% [33, 166]	107% [− 54, 218]	0.830
Overall	**60% [− 30, 118]**	**66% [− 24, 128]**	**0.422**	**52% [− 69, 132]**	**61% [− 38, 143]**	**0.244**	**0.58% [− 29, 120]**	**0.69% [− 18, 142]**	**0.154**
p-value	**0.174**	**0.440**		**0.431**	**0.193**		**0.516**	**0.897**	

P-value: Mann-Whitney U test p-value. Overall p-value: Kruskall-Wallis test p-value for the difference among teeth values

Table 3 Attachment and pressure points used in the study

	Attachments		Pressure points	
	DPA	TFA	DPA	TFA
Incisor				
Superior	0	21	2	5
Inferior	0	0	1	1
Canine				
Superior	0	4	0	0
Inferior	0	4	2	0
Premolar				
Superior	3	2		
Inferior	2	14		
Molar				
Superior	0	0		
Inferior	0	0		
Total	5	45	5	6
% on total teeth	**0.94**	**6.70**	**0.94**	**0.89**

careful hardware maintenance. Furthermore, production quality testing has been shown to be effective in preventing patient issues.This study evaluated accuracy obtained with DPA and compared those results to orthodontic movement accuracy using thermoformed aligners; a total of 74 patients were included and more than 1000 thousand teeth movements were analysed. Generally no statistically significant differences were found between the two groups both for rotation tip and torque values, even though the TFAs showed generally slightly higher accuracy values, this is in accordance with the refinement stages needed to conclude the treatment that were slightly higher for DPAs.

Rotation values accuracy were 58% and 69% for DPA for TFA respectively and the higher values were those for upper premolars, molars and upper incisors for DPA group, while for the TFA group higher accuracy was found for lower incisors and molars. Poor accuracy was registered for lower canines and premolars in the DPA group, while the TFA group values never went under the value of 54% accuracy.

The torque values were the closest between the two groups, and when the TA-28 resin torque accuracy was compared to PETG values, they were essentially the same (65% vs. 66%). The new resin generally showed higher accuracy values when compared to TC-85 resin (Table 3) even though the differences were not statistically significant. 12 out 34 DPA patients used TA-28 resin. Similar torque values were found between the two groups for the canines, while the lateral incisors showed lower values in DPA group (no statistical significant differences).

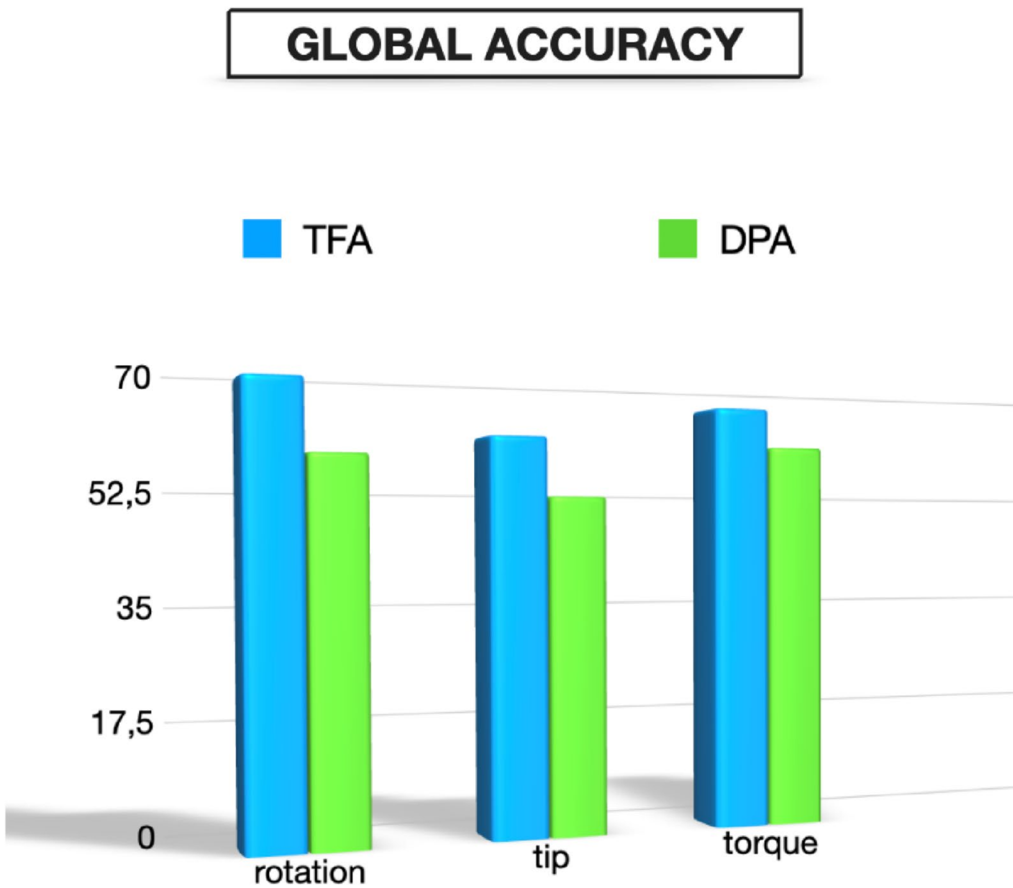

Fig. 3 Global accuracy comparison between DPA and TFA

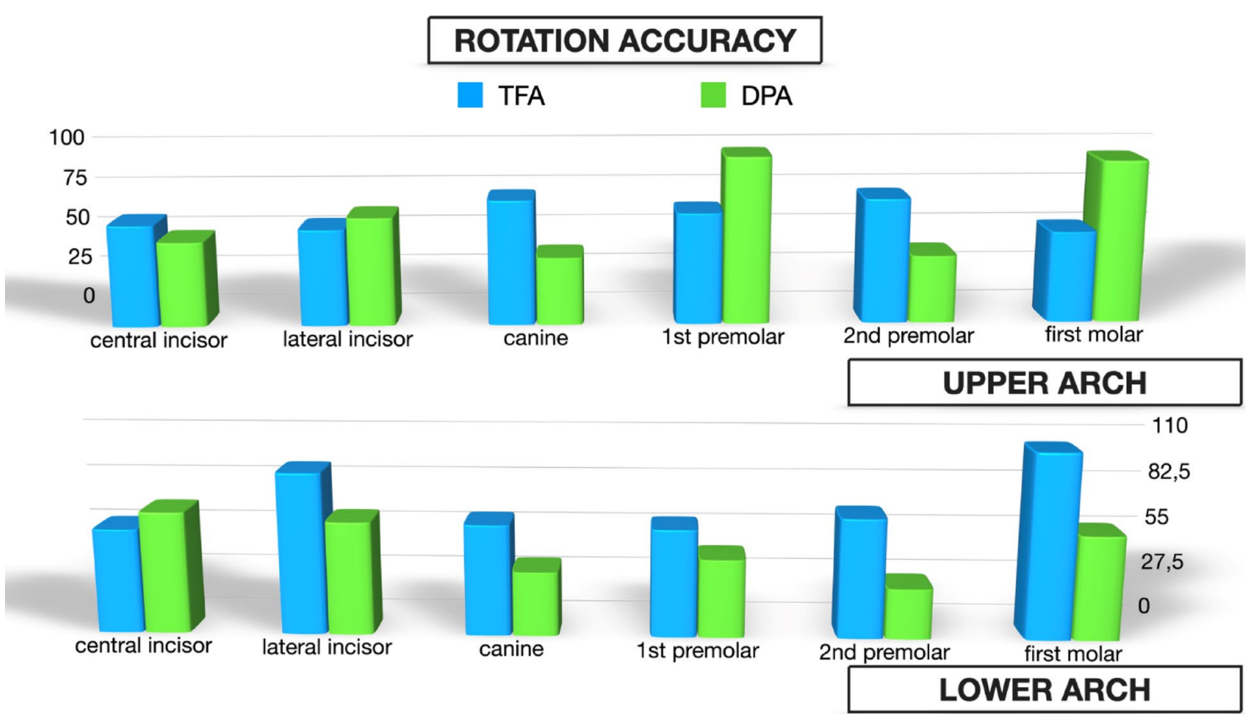

Fig. 4 Rotation accuracy comparison between thermoformed (TFA) and direct printed (DPA) aligners. No statistically significant differences

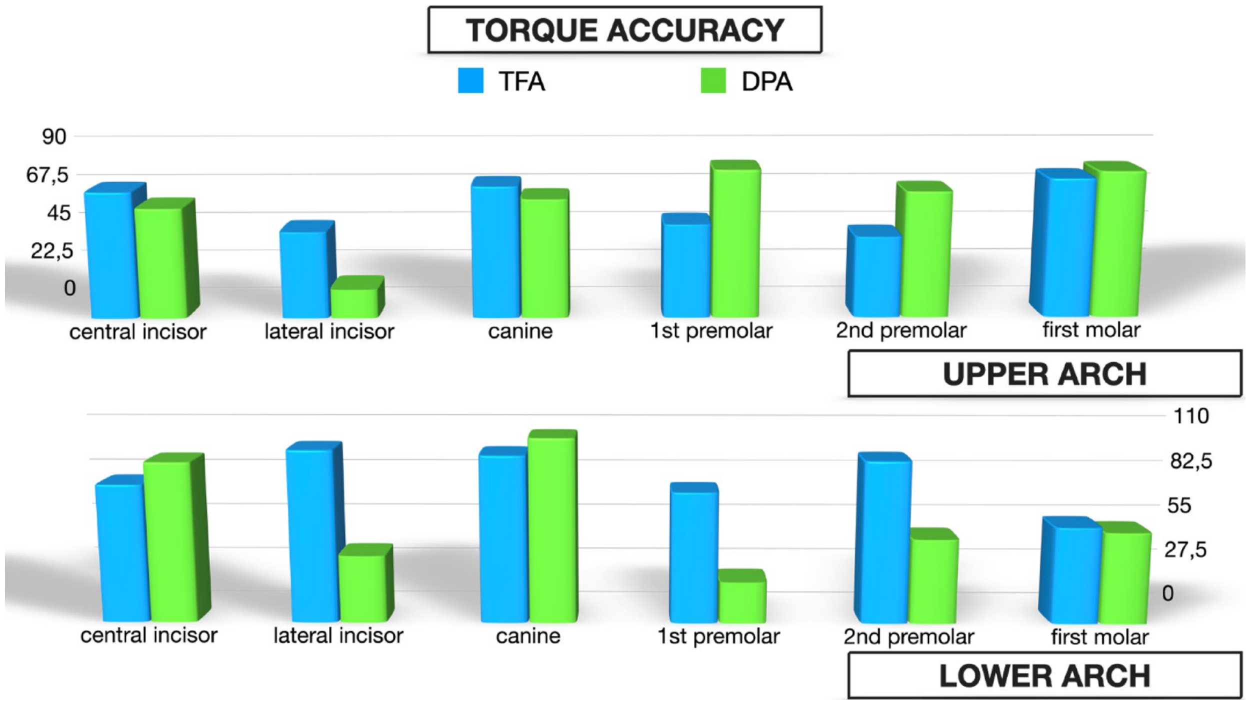

Fig. 5 Torque accuracy comparison between thermoformed (TFA) and direct printed (DPA) aligners. No statistically significant differences

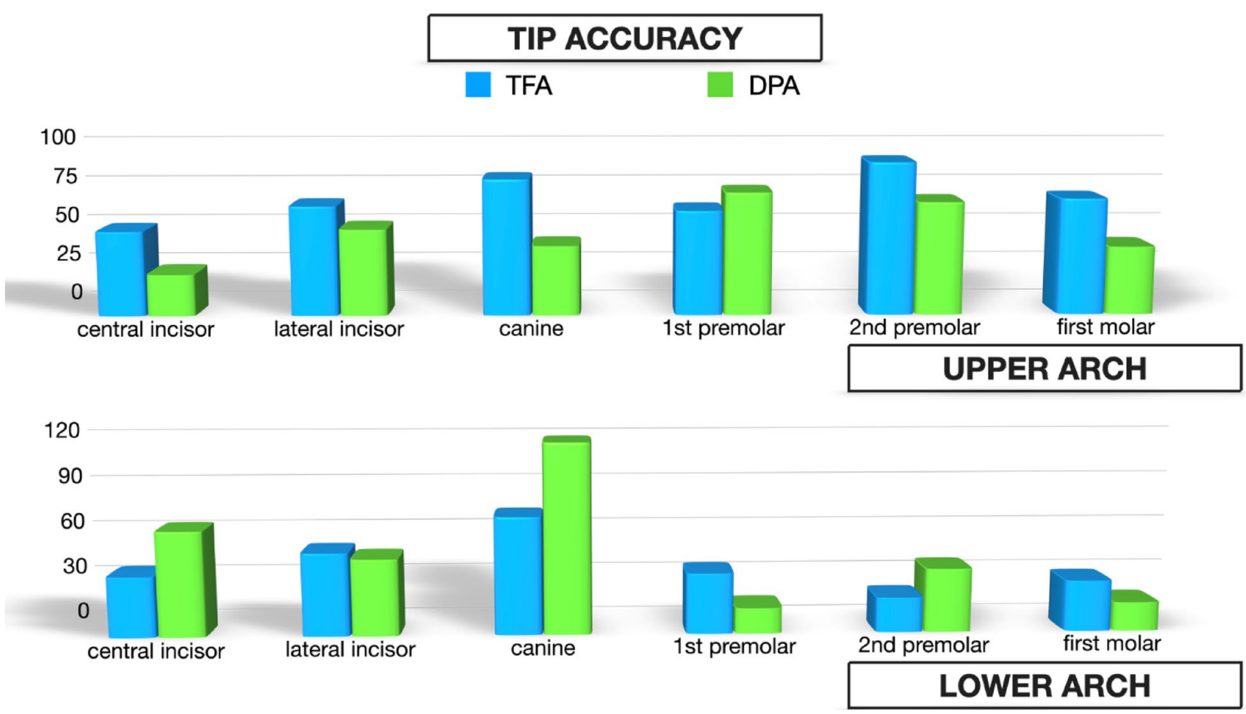

Fig. 6 Tip accuracy comparison between thermoformed (TFA) and direct printed (DPA) aligners. No statistically significant differences

The same trend was observed for tip values with no statistically significant differences.

The only statistically significant difference was found when the three movements' accuracy was evaluated by separating for movement type, and for pure torque movement, without any other components, TFA showed a better result (63% vs. 44%, p-value 0.017, supplementary Table 1).

Other studies in literature found similar or higher values for thermoformed aligners ranging from 50 to 96% [3,

Table 4 Accuracy differences between the two resins used for DPA patients

	TA	TC	*p*-value
Torque accuracy	$n=132$ 65% [− 0.35, 1.75]	$n=312$ 50% [− 0.29, 1.01]	0.071
Tip accuracy	50% [− 0.63, 1.40]	52% [− 0.83, 1.26]	0.807
Rotation accuracy	60% [0.16, 1.44]	58% [− 0.35, 1.10]	0.274

11–13], even though some of these studies included few patients (10 to 16) and small numbers in teeth analysis.

Regarding in office produced aligners, orthodontic accuracy was evaluated by Sachdeve et al. [11] on 30 patients with crowding less than 4 mm, and they found on 259 analyzed teeth an overall accuracy of tooth movement of 56.18%, with the most accurate tooth movement represented by mesiodistal movements (72.33%). In our study the overall accuracy of TFAs was slightly higher (65.3%), while the DPA showed a similar value of 56.7%.

Production process

The traditional thermoformed aligner production process involves the following key steps: Phase 1: Orthodontic Setup: Import of a preliminary intraoral scan into specialized software for segmentation and setup based on clinician specifications. Phase 2: Model Printing: Export of each treatment stage as an STL file for 3D printing. Printing of physical models with necessary support structures. Phase 3: Post-Printing Processing: removal of support structures, washing, and post-curing of the printed models. Phase 4: aligner thermoforming and finishing: tthermoforming aligner material over the printed models, trimming, and conducting quality checks.

The direct printed aligner production process shares similar steps with slight variations. Phase 1: Digital Aligner Design: while the initial steps are similar to thermoformed aligners, the key difference lies in the design phase. Here, clinicians can directly manipulate geometric aspects (e.g., thickness) and the overall aligner design based on specific biomechanical requirements. In this phase different studies have shown how strategic variations in aligner thickness can produce improvement both in anchorage and force and moment expressed by the aligner [5, 14, 15]. Phase 2: Aligner Printing: Direct printing of the aligners using appropriate 3D printing technology. Phase 3: Post-Curing and Verification: This involves removing excess resin using a centrifuge and employing specific curing units to ensure complete polymerization. Following curing, a washing step is performed, and a mandatory one-minute immersion in boiling water is carried out to verify proper resin polymerization. Phase 4: Quality Check: Final inspection of the printed aligners.

Both production processes require careful management and ideally a dedicated, trained individual to oversee all hardware and software operations. Different hardware and software choices can impact key dependent variables, including maintenance time and costs, production time, aligner output per time unit, and the efficiency of the entire digital process. However, the resulting aligners are expected to exhibit similar characteristics. The rapid evolution of both software and hardware is expected to

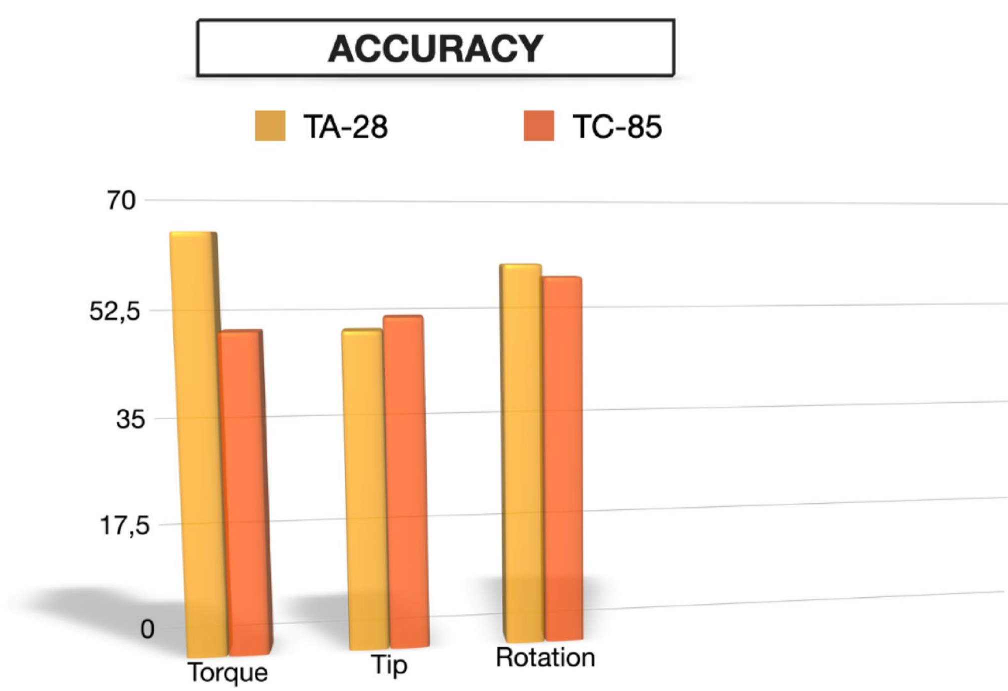

Fig. 7 Accuracy comparison between TA-28 and TC-85 resin

gradually streamline this entire workflow, enabling highly efficient in-office production of both DPAs and TFAs.

Production time was similar to those already reported [9], with 40 min post-printing production time needed for 8 DPA and more than 100 min for the same numbers of TFAs. These data are strictly related to the hardware and software used in this study and can vary.

Considering the in-office production workflow and clinical management, two aspects deserve a deepening. First is about the setup and number of aligners produced for both groups. From an efficiency standpoint, producing fewer aligners per batch (e.g., no more than 10–12, even if the total treatment requires more) is more productive than large productions exceeding 15–20 aligners. Usually, no more than 10–12 aligners were produced each time, even though the original setup included more aligners. This because after the first set of aligners was delivered, it was possible to clinically evaluate if a proper aligner fitting was achieved: if the fit was satisfactory, the subsequent aligners were produced. If not, a new intraoral scan was taken, and a revised setup was completed. This strategy, implemented for both patient cohorts, significantly reduces material waste and optimizes patient treatment time.

The second point is about the use of attachments and pressure points; in TFA 's patients attachment were used seven times more when compared to DPA patients (Table 4), in DPA group patients were treated with limited use of attachment, mostly for retention (5 attachments in total); for rotation of anterior teeth pressure points/area were used as standard choice instead of attachments; this difference could eventually explain the slightly lower accuracy rate observed in DPA. This approach can help reduce chair time and avoid attachments in both groups. From a clinical perspective, the experience gained so far emphasizes that the importance of attachments and pressure points is as valuable as a good strategic setup.

Limitations

The limits of the present study include the measurement procedure that requires a skilled operator and proper software to reduce difficulties related to teeth with abrasion or abnormally shaped and altered planes.

Further studies are necessary to understand how the presence of attachment or pressure points can affect the accuracy of results for both therapy options.

Generalizability

This study highlighted the clinical applications of DPA in a daily routine, comparing the dental movement effect with a traditional material such as the PTE-G (in office workflow). The detailed production procedures described in this study represent a standard for in-office workflows. Orthodontists who precisely follow this process can expect to achieve results with a consistency comparable to that of traditional aligner setup and staging protocols.

A key advantage of the DPA system is its capacity for high individualization through strategic 3D planning for specific patient needs. However, clinical studies are required to confirm whether this enhanced customization leads to superior therapeutic outcomes.

Conclusions

Within the limits of the study, it was possible to compare the orthodontic accuracy movement obtained with thermoformed and direct printed aligners produced in office.

No statistically significant differences were found between the two groups in respect of rotation, tip and torque movements.

The overall accuracy of the torque was 60% and 66% for the DPA and TFA group respectively.

The overall accuracy of the tip was 52% and 61% for the DPA and TFA group respectively.

The overall accuracy for rotations was 58% and 69% for the DPA and TFA group respectively.

All treatments were successfully completed with similar amounts of refinement stages.

Abbreviations

DPA Direct printed aligners
TFA Thermoformed aligners
STL Standard triangle language
PETG Polyethylene terephthalate glycol

Supplementary Information

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Supplementary Material 1

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Author contributions

MM: wrote the manuscript, conception, study design, clinical cases management. MP: data analysis. CP: data collection and figures. ADM: data analysis, software. SD: statitiscal analysis. All authors reviewed the manuscript.

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Data availability

Available upon a reasonable request.

Declarations

Ethics approval and consent to participate

Ethical Committee (No. 2025/2, University of Genova, Genova, Italy).

Consent for publication

Not applicable.

Competing interests

MM has previously received payment or honoraria for giving lectures or presentations. This compensation came from an Italian reseller, not from the company that produces 3D printed aligners. All other authors have no disclosures to make.

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