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A comparative assessment of the dentoskeletal effects of clear aligners vs miniplate-supported posterior intrusion with fixed appliances in adult patients with anterior open bite. A multicenter, retrospective cohort study

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Introduction: This study aimed to retrospectively evaluate the dentoskeletal effects of clear aligners (Invisalign) vs miniplate-supported posterior intrusion (MSPI) and identify factors associated with posttreatment overbite in adults with anterior open bite. **Methods:** Twenty-nine patients treated with Invisalign and 24 with MSPI combined with full-fixed orthodontic appliances were included from 5 orthodontic practices. Pretreatment and posttreatment lateral cephalometric measurements were included as outcomes. Comparisons across groups and identification of final overbite predictors were assessed with regression modeling and machine learning techniques. **Results:** MSPI induced significantly greater maxillary molar intrusion (1.5 mm; 95% confidence interval [CI], 0.83-2.17; $P<0.001$), with subsequent reduction of anterior face height (ANS-Me) (−2.77 mm; 95% CI, −3.64 to −1.91; $P<0.001$), Mp-SN° (−1.95°; 95% CI, −2.77 to −1.12; $P<0.001$), and ANB° (−1.69°; 95% CI, −2.44 to −0.94; $P<0.001$) compared with Invisalign. MSPI resulted in a significantly larger increase in SNB° (0.94°; 95% CI, 0.23-1.65; $P=0.01$) and point-Pog projection (2.45 mm; 95% CI, 1.12-3.77; $P=0.001$). Compared with MSPI, Invisalign had a significantly greater increase in the distance of maxillary (1.05 mm; 95% CI, 0.38-1.72; $P=0.003$) and mandibular (0.9 mm; 95% CI, 0.19-1.60; P = 0.01) incisal edges relative to their apical bases, with borderline greater lingual tipping of only the maxillary incisors (2.82°; 95% CI, −0.44 to 6.09; $P=0.09$). Appliance type and initial overbite were significant final overbite predictors across all models. However, this difference was only evident in male patients (males [1.65; 95% CI, 0.99-2.32; $P<0.001$]; female [−0.04; 95% CI, −0.52 to 0.44; $P=0.87$]). **Conclusions:** Both appliances effectively improve overbite. MSPI applied the correction via molar intrusion and counterclockwise mandibular autorotation, whereas Invisalign via maxillary and mandibular incisor extrusion. (Am J Orthod Dentofacial Orthop 2022;■:■-■)

Background

Skeletal open bite malocclusion presents with the challenging combination of an anterior open bite (AOB) on a hyperdivergent skeletal base while a disproportionately elongated lower face height, a steep mandibular plane (MP), and increased maxillary gingival display on smiling are within the accompanying characteristic features of this malocclusion.[1-3] In adult patients, orthognathic surgery has been traditionally advocated as an effective means of addressing the underlying skeletal dysplasia while

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avoiding undue incisor extrusion.[2-4] This commonly involves maxillary impaction with a LeFort I osteotomy. After the maxillary impaction, a passive forward autorotation of the mandible reduces the lower anterior face height (ANS-Me) and the open bite.[4] It is believed that successful camouflage treatment with the intrusion of the dental buccal segments can produce comparable treatment effects to orthognathic surgery.[5] Miniplate-supported posterior intrusion (MSPI)[6-13] and clear aligner therapy using Invisalign[14-19] have independently emerged as promising camouflage options. These approaches can circumvent much of the cost, complexity, procedural risk, and morbidity inherent with orthognathic surgery.[20-22]

Skeletal plates can provide absolute anchorage for posterior dental intrusion[6,7] and are generally well tolerated by patients.[23] Compared with miniscrews, skeletal plates confer superior survival rates,[24,25] are less prone to anchorage loss,[26] and allow for heavier and more complex biomechanical force systems.[8] Influenced by the seminal work of Umemori et al,[8] several studies have confirmed the effectiveness of open bite closure when miniplates are used in the maxilla[5,6,9-12] or mandible.[7] Placing 1 miniplate in all 4 quadrants has been suggested to maximize the combined amount of intrusion obtained while mitigating any potential extrusion in the opposing arch.[5,13] Using the 1 miniplate per quadrant configuration, Kuroda et al[5] reported in a small sample of a primarily adult population with severe AOB malocclusions, 100% overbite correction with minimal incisor extrusion. An average molar intrusion of approximately 2.3 mm in the maxillary and 1.3 mm in the mandibular molar region was achieved. The resultant mandibular autorotation and facial changes obtained were comparable to those in a matched orthognathic surgery group.

The clinical application of Invisalign for AOB treatment was proposed after anecdotal observations of a frequently developed bilateral posterior open bite during treatment. This led some clinicians to hypothesize that an intrusive posterior bite-block effect is present as the aligner material is interposed on the interocclusal spaces and under the activity of the elevator masticatory musculature.[14] A few patient studies have demonstrated treatment effects consistent with this theory. However, the validity and clinical significance of their findings are uncertain.[18,19] Collective evidence from 4 recent retrospective case series suggests that the relative contribution of incisor extrusion and lingual tipping vs molar intrusion is unclear. It appears at present that any potential molar intrusion with Invisalign is likely minimal and insufficient to manifest as an appreciable reduction in lower face height.[16-19]

Objectives

To our knowledge, no study has directly evaluated the comparative effectiveness of MSPI vs Invisalign in adults with an open bite. Therefore, this study aimed to compare the dentoskeletal effects of the 2 treatment modalities and the underlying mechanism for achieving overbite correction. In addition, predictive models for identifying factors that had a significant effect in post-treatment overbite were fit. The null hypothesis is no differences with skeletal (vertical and anteroposterior) and dental treatment-induced changes between MSPI and Invisalign. Reporting of the present study follows the Strengthening the Reporting of Observational Studies in Epidemiology statement.

MATERIAL AND METHODS

Study design

This multicenter, retrospective cohort study was approved by the Human Research Ethics committee of the Sydney Local Health District, RPAH Zone (Ethics approval no. X18-0352).

Setting and participants

The study sample was retrospectively collected from the records of adult patients consecutively treated with either posterior miniplates and full-fixed appliances (MSPI group) or clear aligners (Invisalign group) across 5 private orthodontic practices in Australia (4 located in Sydney and 1 in Adelaide). The 5 treating orthodontists were registered specialists with >10 years of clinical experience using the examined appliance systems. The MSPI group was treated by 2 orthodontists (10 and 14 patients included from each practice), and the Invisalign group was treated by 3 orthodontists (5, 8, and 16 patients from each practice) who were, at a minimum, Invisalign Platinum Elite providers, treating >80 patients per year.

To qualify for inclusion in the study, all the following eligibility criteria had to be met:

1. Patients were aged >18 years at the commencement of treatment to minimize any potential confounding growth effects.
2. Treatment was completed between April 2014 and April 2020 (corresponding to Align's introduction of the G4 treatment algorithm for open bite treatment [2011][27] and SmartTrack aligner material [Align Technology, Santa Clara, Calif] [2013], both of which remain in use today).[28]
3. No vertical overlap between the maxillary and mandibular incisors as determined by the distance between the maxillary and mandibular incisal edges measured at a perpendicular to the occlusal

plane (defined by the mesiobuccal cusp tips of the maxillary and mandibular first molars to the bisecting point between the maxillary and mandibular incisor edges) on a lateral cephalogram and validated by pretreatment frontal intraoral photographs.

4. Edge-to-edge canines were acceptable.
5. Treatment was performed exclusively using 1 of the 2 described treatment modalities (ie, MSPI or Invisalign).
6. For the MSPI group, patients who received surgically assisted rapid maxillary expansion (SARME) at the time of miniplate placement were included.
7. Patients with >3 separate treatment refinements were excluded in the Invisalign group.
8. No extractions (excluding third molars) were performed.
9. The intraarch crowding did not exceed 6 mm in either arch.
10. The anteroposterior dental correction did not exceed a half unit in any direction.
11. Pretreatment and posttreatment lateral cephalograms of acceptable diagnostic quality were obtained within 2 months of treatment initiation and completion.

For the MSPI group, 1 miniplate was placed in each quadrant in both jaws at the level of the first molars. Miniplates were loaded 4-6 weeks after their surgical placement. During the miniplates' stabilization period, SARME was performed on patients who required this adjunctive procedure. A rigid cross-arch stabilization appliance was in situ in each arch (rapid maxillary expansion, transpalatal arch, or lower lingual arch), along with fixed appliances. The incisors were bypassed, or segmental mechanics were used on a discretionary, patient-by-patient basis. The miniplates must have remained stable and clinically useful for the overall duration of treatment. For the Invisalign group, open bite correction was prescribed in the Clinchecks as a combination of posterior intrusion and anterior extrusion.

Variables and measurement

Pretreatment (T1) and posttreatment (T2) lateral cephalograms were deidentified and coded to be blindly traced and measured by a single investigator (B.P.S.) with magnification adjusted for each image using proprietary cephalometric analysis software (version 11.9; Dolphin Imaging and Management Solutions, Chatsworth, Calif). Landmarks were located sequentially for each patient to minimize the potential for identification errors. Based on a custom cephalometric analysis including elements from Steiner, Downs, Harvold, and Sassouni, 9 linear (Supplementary Fig 1) and 11 angular (Supplementary Fig 2) measurements were calculated. Sella-Nasion (SN), palatal (PP), occlusal plane, MP, and a constructed x and y coordinate system were used as reference planes. The coordinate system was constructed by a horizontal line, which formed a 7° angle with SN-line and represented the horizontal reference plane, and a perpendicular to horizontal reference plane projected from point Sella and representing the vertical reference plane (Supplementary Fig 1). The definition of the cephalometric measurements is outlined in the Supplementary Table.

For method error analysis, 1 month after the initial cephalograms were traced, 25% of the sample from each group was randomly selected using the random number generator in Excel (Microsoft, Redmond, Wash). The T1 and T2 cephalograms had all landmarks re-identified by the same investigator (B.P.S.), and the measurements were recalculated using the Dolphin Imaging software. Intraexaminer reliability was assessed using the intraclass correlation coefficient.

Bias

A single investigator (B.P.S.) screened consecutively treated patient records from each practice. The records from all consecutively treated patients in each practice were screened with access to the Invisalign accounts given to the investigators to minimize potential selection bias by the clinicians involved in the treatment of patients. In addition, to minimize any potential confounding effects arising from different clear aligner systems, only patients who received Invisalign were included in this group. Each eligible patient was assigned a unique code for record deidentification purposes. The collected records consisted of demographic information (date of birth, sex), relevant clinical notes (treatment performed, commencement, and completion of treatment dates), T1 intraoral photographs (frontal and sagittal), and T1 and T2 lateral cephalograms. For the Invisalign group, the Invisalign treatment overview form (detailing the number of aligners), planned interproximal reduction, and type and location of bonded attachments were available.

Study size

A sample size calculation was performed using the ANS-Me as the variable of interest for both patients and clinicians. Because an overbite could invariably be corrected with both modalities, it was not chosen as the sample size calculation defining outcome. In addition, changes in overbite do not directly reflect the mode of action of each treatment modality, whereas

Table I. Demographics of MSPI and Invisalign groups

Demographics	*MSPI*	*Invisalign*
Age at T1, y		
Mean ± SD	27.1 ± 8.32	28.94 ± 9.12
Range	18.8-44.8	18.4-59.0
Gender (% female)	54.2	75.86
Duration of treatment, mo, median (IQR)	29.39 (10.38)	19.75 (13.01)
No. of teeth in AOB	7.36 (2.63)	6.69 (2.58)
No. of aligners		57.69 (25.92)
Maxillary IPR, mm, mean ± SD		0.44 ± 0.72
Mandibular IPR, mm, mean ± SD		1.70 ± 1.75
Total IPR, mm, mean ± SD		2.14 ± 2.07

SD, standard deviation; *IQR*, interquartile range.

changes in the ANS-Me indirectly incorporate changes pertinent to the intrusion of buccal segments and mandibular autorotation. Values for ANS-Me changes using MSPI (−3.57 ± 1.15 mm)[16] and Invisalign (−0.17 ± 1.6 mm)[20] were retrieved from previous studies. Based on these ANS-Me changes due to treatment and considering a clinically meaningful difference of 3.4 ± 1.5 mm between arms for this variable, a total of 34 patients were required to detect such a difference with 95% power and at 5% significance level.[29]

Statistical analysis

Descriptive statistics (means and standard deviations) were calculated for the cephalometric variables on the T1 and T2 radiographs in both groups. The log-rank test and Kaplan-Meier plot were used to compare treatment duration between the 2 groups. Initially, a series of analyses of covariance were used to examine associations between the cephalometric measurements at T2 and type of treatment after adjusting for their T1 outcome value. On an exploratory basis, the effect of T1 variables on the final overbite was examined using regression modeling and machine learning techniques. Manual selection and stepwise backward elimination were performed to identify significant predictors for overbite at T2 using an α threshold of 0.1 and 0.2, respectively. A generalized additive model (GAM) algorithm was implemented using the step.gam function (GAM package in R) and the selected parameters were included in an additive model using the GAM function from the MGCV package in R. In the step.gam function, all variables and corresponding splines up to 2 degrees of freedom were included. Smoothness optimization when fitting the final model was achieved via restricted maximum likelihood. The final GAM model selection was further reduced on the basis of deviance explained and the Akaike information criterion (AIC). Results among

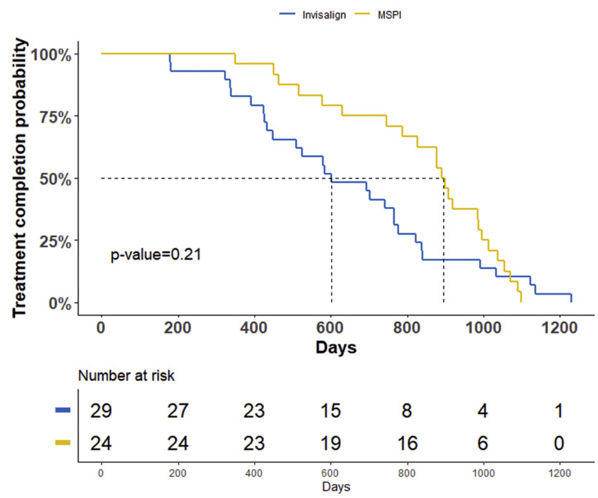

Fig 1. Kaplan-Meier survival plot for treatment duration for Invisalign and MSPI groups.

the 3 variable selection models were compared using the AIC fit statistic criterion, percentage deviance explained, and analysis of variance. Finally, to identify important posttreatment overbite predictors, the generalized boosted regression modeling (GBM) approach was implemented using the GBM function in the R software. The best iteration algorithm was selected using 10-fold cross-validation over a grid for interaction depth, a minimum number of observations per node, and shrinkage. All analyses were conducted with Stata (version 16.1; Stata Corp, College Station, Tex) and R software (version 3.6.1; R Foundation for Statistical Computing, Vienna, Austria) with a 2-sided 5% level of statistical significance and the dataset openly provided in Zenodo.[30]

RESULTS

Participants and descriptive data

The final sample consisted of 24 patients in the MSPI group (4 received SARME) and 29 patients in the Invisalign group. Groups were similar regarding age and number of teeth in AOB, whereas treatment duration was shorter with Invisalign but not significantly different (log-rank test, $P = 0.21$) (Table I; Fig 1). The intraclass correlation coefficient ranged between 0.97 and 0.99, showing excellent reliability.

Outcome data, main results, and other analyses

Descriptive statistics for the cephalometric values with the changes induced within and between treatment groups are reported in Table II.

Table II. T1, T2, and T2 − T1 for MSPI and Invisalign groups

Variables	*MSPI* T1	*MSPI* T2	*MSPI* T2 − T1	*Invisalign* T1	*Invisalign* T2	*Invisalign* T2 − T1	*Invisalign − MSPI* T1	*Invisalign − MSPI* T2
Vertical								
N-ANS, mm	51.21 ± 3.2	51.35 ± 3.16	0.13 ± 0.53	50.81 ± 6.05	50.88 ± 6.16	0.07 ± 0.4	−0.4 ± 4.96	−0.47 ± 5.03
ANS-Me, mm	75.63 ± 6.51	72.73 ± 6.19	−2.9 ± 1.85	71.72 ± 11.13	71.68 ± 11.15	−0.04 ± 1.2	−3.91 ± 9.35	−1.05 ± 9.24
SN-PP, °	4.98 ± 4.41	5.27 ± 4.52	0.28 ± 0.93	5.86 ± 3.06	5.9 ± 3.08	0.04 ± 0.79	0.88 ± 3.73	0.64 ± 3.81
SN-Go-Me, °	40.94 ± 5.99	38.75 ± 5.58	−2.19 ± 1.89	39.52 ± 6.97	39.36 ± 6.91	−0.16 ± 1.11	−1.42 ± 6.56	0.61 ± 6.34
SN-OP, °	17.87 ± 3.98	18.95 ± 4.9	1.08 ± 3.1	16.08 ± 5.60	17.03 ± 5.18	0.95 ± 2.07	−1.79 ± 4.93	−1.92 ± 5.07
Y-axis, °	72.46 ± 4.04	70.81 ± 3.89	−1.65 ± 1.52	69.91 ± 4.9	60.70 ± 4.64	−0.21 ± 0.85	−2.55 ± 4.53	−1.11 ± 4.31
Facial axis, °	84.6 ± 4.3	86.02 ± 4.5	1.42 ± 2.2	87.86 ± 4.99	87.77 ± 5.09	−0.09 ± 1.39	3.26 ± 4.67	1.75 ± 4.82
OB, mm	−3.03 ± 1.7	0.93 ± 0.87	3.96 ± 1.52	−2.18 ± 1.38	0.60 ± 0.95	2.78 ± 1.15	0.85 ± 1.52	−0.33 ± 0.91
Sagittal								
SNA, °	80.92 ± 3.64	80.41 ± 4.77	−0.51 ± 1.47	81.70 ± 3.21	81.86 ± 3.57	0.16 ± 1.25	0.78 ± 3.41	1.45 ± 4.13
SNB, °	76.68 ± 3.97	77.64 ± 4.04	0.96 ± 1.48	78.65 ± 3.71	78.54 ± 3.56	−0.11 ± 1.02	1.97 ± 3.84	0.9 ± 3.77
ANB, °	4.23 ± 3.17	2.76 ± 3.66	−1.47 ± 1.47	3.04 ± 2.76	3.32 ± 2.61	0.27 ± 1.18	−1.18 ± 2.94	0.55 ± 3.12
Facial angle, °	87.27 ± 4.05	87.83 ± 4.13	1.56 ± 1.4	88.18 ± 4.25	88.42 ± 4.06	0.24 ± 0.76	1.92 ± 4.17	0.6 ± 4.09
VRP-Pog, mm	55.88 ± 9.87	58.95 ± 9.96	3.06 ± 2.91	60.09 ± 12.35	60.55 ± 11.99	0.46 ± 1.79	4.21 ± 11.31	1.6 ± 11.13
OJ, mm	3.88 ± 2.55	3.01 ± 0.84	−0.87 ± 2.59	3.18 ± 2.09	2.33 ± 1.1	−0.86 ± 1.44	−0.7 ± 2.32	−0.68 ± 0.98
Molar position								
PP-U6, mm	26.18 ± 2.46	24.36 ± 2.74	−1.82 ± 1.51	25.42 ± 4.56	25.13 ± 4.53	−0.3 ± 0.88	−0.75 ± 3.77	0.77 ± 3.84
L6-MP, mm	34.43 ± 4.07	33.68 ± 3.75	−0.74 ± 1.39	31.24 ± 4.96	31.23 ± 5.2	−0.01 ± 1.75	−3.18 ± 4.57	−2.45 ± 4.6
Incisor position								
PP-U1, mm	31.54 ± 3.7	31.99 ± 3.83	0.45 ± 1.54	30.23 ± 5.07	31.72 ± 5.31	1.48 ± 0.79	−1.3 ± 4.49	−0.27 ± 4.71
U1-PP, °	110.38 ± 8.32	109.46 ± 6.45	−0.92 ± 8.3	114.01 ± 5.76	108.16 ± 6.29	−5.85 ± 5.64	3.62 ± 7.03	−1.31 ± 6.38
Mp-L1, mm	42.49 ± 4.45	42.54 ± 4.48	0.05 ± 1.5	40.39 ± 5.72	41.38 ± 5.79	0.99 ± 0.96	−2.1 ± 5.18	−1.17 ± 5.25
L1-Mp, °	92.33 ± 9.9	91.2 ± 8.81	−1.13 ± 5.88	91.24 ± 8.37	90.71 ± 6.85	−0.53 ± 5.52	−1.08 ± 9.1	−0.48 ± 7.79

Note. Values are mean ± standard deviation.

Table III. Linear regression on for the effect of treatment on the recorded variables at T2 accounting for T1 outcome values

Variable	*b coefficient*	*95% CI*	*P value*
Vertical			
N-ANS at T2, mm			
Invisalign	Reference		
MSPI	0.06	−0.2 to 0.32	0.64
N-ANS at T1 per mm	1.01	0.98-1.03	<0.001
ANS-Me at T2, mm			
Invisalign	Reference		
MSPI	−2.77	−3.64 to −1.91	<0.001
ANS-Me at T1 per mm	0.98	0.93-1.02	<0.001
SN-PP at T2, °			
Invisalign	Reference		
MSPI	0.24	−0.24 to 0.72	0.33
SN-PP at T1 per degree, °	0.99	0.93-1.06	<0.001
SN-Go-Me at T2, °			
Invisalign	Reference		
MSPI	−1.95	−2.77 to −1.12	<0.001
SN-Go-Me at T1 per degree, °	0.94	0.88-1.01	<0.001
SN-OP at T2, °			
Invisalign	Reference		
MSPI	0.33	−1.11 to 1.77	0.65
SN-OP at T1 per degree, °	0.88	0.74-1.03	<0.001
Y-axis, °			
Invisalign	Reference		
MSPI	−1.23	−1.9 to −0.57	<0.001
Y-axis at T1 per mm	0.92	0.85-0.99	<0.001
Facial axis, °			
Invisalign	Reference		
MSPI	1.36	0.30-2.43	0.013
Facial axis at T1 per degree, °	0.97	0.85-1.06	<0.001
OB at T2, mm			
Invisalign	Reference		
MSPI	0.58	0.12-1.04	0.01
OB at T1 per mm	0.30	0.16-0.45	<0.001
Sagittal			
SNA at T2, °			
Invisalign	Reference		
MSPI	−0.54	−1.24 to 0.15	0.12
SNA at T1 per degree, °	1.16	1.06-1.26	<0.001
SNB at T2, °			
Invisalign	Reference		
MSPI	0.94	0.23-1.65	0.01
SNB at T1 per degree, °	0.94	0.84-1.03	<0.001
ANB at T2, °			
Invisalign	Reference		
MSPI	−1.69	−2.44 to −0.94	<0.001
ANB at T1 per degree, °	0.96	0.84-1.09	<0.001
Facial angle, °			
Invisalign	Reference		
MSPI	1.22	0.6-1.84	<0.001
Facial angle at T1 per degree, °	0.95	0.87-1.02	<0.001
VRP-Pog at T2, mm			
Invisalign	Reference		
MSPI	2.45	1.12-3.77	<0.001
VRP-Pog at T1, per mm	0.96	0.90-1.02	<0.001
OJ at T2, mm			
Invisalign	Reference		
MSPI	0.54	0.05-1.04	0.03
OJ at T1, per mm	0.20	0.09-0.31	<0.001

Table III. Continued

Variable	b coefficient	95% CI	P value
Molar position			
PP-U6 at T2, mm			
Invisalign	Reference		
MSPI	−1.50	−2.17 to −0.83	<0.001
PP-U6 at T1, per mm	0.97	0.88-1.06	<0.001
L6-MP at T2, mm			
Invisalign	Reference		
MSPI	−0.55	−1.48 to 0.39	0.25
L6-MP at T1, per mm	0.94	0.85-1.04	<0.001
Incisor position			
PP-U1 at T2, mm			
Invisalign	Reference		
MSPI	−1.05	−1.72 to −0.38	<0.01
PP-U1 at T1, per mm	1.01	0.93-1.09	<0.001
U1-PP at T2, °			
Invisalign	Reference		
MSPI	2.82	−0.44 to 6.09	0.09
U1-PP at T1 per degree, °	0.42	0.19-0.65	0.001
Mp-L1 at T2, mm			
Invisalign	Reference		
MSPI	−0.90	−1.6 to −0.19	0.01
Mp-L1 at T1, per mm	0.98	0.91-1.05	<0.001
L1-Mp at T2, °			
Invisalign	Reference		
MSPI	−0.25	−2.96 to 2.47	0.86
L1-Mp at T1 per degree, °	0.67	0.52-0.82	<0.001

Note. Statistical significance set at the $P < 0.05$.

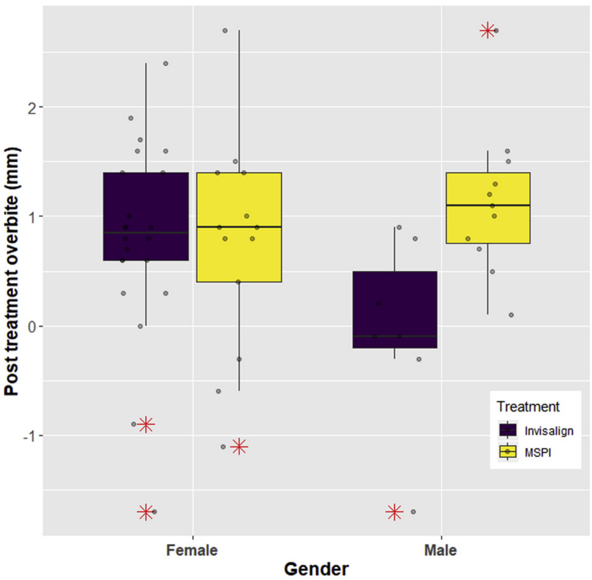

Fig 2. Boxplots for posttreatment overbite by gender and treatment.

At T1, the MSPI group had on average an overbite of 1 mm, SNB angle of 2°, and horizontal projection of point-Pog of 4 mm less than Invisalign. The perpendicular distance of the mandibular first molars to the MP (L6-MP) and the lower ANS-Me were 3 and 4 mm greater in the MSPI group. Those differences indicated a less severe malocclusion for the Invisalign group at T1.

Linear regression for the effect of treatment type on the variables at T2 after adjusting for their T1 values is presented in Table III. The densities of the variables are shown in Supplementary Figure 3.

MSPI was significantly associated with a greater reduction in ANS-Me (−2.77 mm; 95% confidence interval [CI], −3.64, −1.91), Mp-SN° (−1.95°; 95% CI, −2.77 to −1.12), y-axis° (−1.23; 95% CI, −1.9 to −0.57), ANB° (−1.69°; 95% CI, −2.44 to −0.94) and the distance of the maxillary molars to their apical base PP-U6 (−1.5 mm; 95% CI, −2.17 to −0.83), depicting the intrusion effect. Similarly, MSPI was associated with a greater reduction in SNA°, L6-MP, and L1-Mp° by −0.54° (95% CI, −1.24 to 0.15), −0.55 mm (95% CI, −1.48 to 0.39) and −0.25° (95% CI, −2.96 to 2.47) respectively compared with Invisalign. However, these differences were of limited clinical value and not statistically significant. The changes in the distance of the maxillary PP-U1 (−1.05 mm; 95% CI, −1.72 to −0.38) and mandibular Mp-L1 (−0.9 mm; 95% CI, −1.6 to −0.19) incisal edges relative to their

Table IV. Estimates, 95% CI, and *P* values from the explorative multivariable regression analysis for significant predictor selection for T2 overbite using stepwise backward elimination, manual selection, and GAM

Factor	*Category*	*b (95% CI)*	P *value*	*AIC (deviance explained)*
Stepwise backward elimination (0.2 α threshold-20%)				113.95 (55.3%)
SNA at T1, °	Per degree, °	0.09 (0.02-0.18)	0.02	
SNB at T1, °	Per degree, °	−0.12 (−0.19 to −0.04)	0.01	
OB at T1, mm	Per mm	0.43 (0.03-0.57)	<0.001	
Treatment	Invisalign	Reference		
	MSPI	−0.04 (−0.52 to 0.54)	0.87	
Gender	Female	Reference		
	Male	−0.90 (1.48 to −0.31)	<0.01	
Treatment × gender		1.69 (0.88-2.50)	<0.001	
Manual variable selection (0.1 α threshold-10%)				118.18 (56.8%)
SNB at T1, °	Per degree, °	−0.04 (−0.15 to 0.07)	0.48	
U1-PP at T1, °	Per degree, °	0.01 (−0.02 to 0.04)	0.66	
OB at T1, mm	Per mm	0.40 (0.24-0.56)	<0.001	
Y-axis at T1, °	Per degree, °	0.02 (−0.09 to 0.12)	0.74	
L6-MP at T1, mm	Per mm	0.01 (−0.05 to 0.06)	0.82	
Treatment	Invisalign	Reference		
	MSPI	−0.02 (−0.55 to 0.52)	0.94	
Gender	Female	Reference		
	Male	−1.04 (−1.73 to −0.36)	<0.01	
Treatment × gender		1.76 (0.88-2.65)	<0.001	
GAM				106.273 (76.6%)
U1-PP at T1, °	Per degree, °	−0.03 (0.02)	0.11	
N-ANS at T1, mm	Per mm	−0.04 (0.03)	0.25	
SN-PP at T1, °	Per degree, °	0.10 (0.04)	0.01	
OB at T1, mm	Per mm	0.31 (0.06)	<0.001	
Facial angle at T1, °	Per degree, °	−0.07 (0.03)	0.04	
L1-Go-Me at T1, mm	Per mm	0.10 (0.04)	0.03	
Treatment	Invisalign	Reference		
	MSPI	0.09 (0.22)	0.68	
Gender	Female	Reference		
	Male	−1.01 (0.32)	<0.01	
Treatment × gender		1.79 (0.39)	<0.001	
Approximate significance of smooth terms				
	Estimated df	Reference df		
s(L1-Mp at T1), °	3.69	4.80	0.03	
s(L6-MP at T1), mm	3.01	3.86	0.03	
s(VRP-Pog at T1), mm	1.40	1.67	0.17	

df, degrees of freedom.

apical bases were significantly less in MSPI than Invisalign. MSPI was associated with a significantly greater change in OB (0.58 mm; 95% CI, 0.12-1.04), facial axis° (1.36; 95% CI, 0.30-2.43), OJ (0.54 mm; 95% CI, 0.05-1.04), SNB° (0.94°; 95% CI, 0.23-1.65), facial angle (1.22; 95% CI, 0.60-1.84), and vertical reference plane-Pog (2.45 mm; 95% CI, 1.12-3.77) compared with Invisalign. Furthermore, Invisalign was associated with a greater reduction in the inclination of the maxillary incisors U1-PP° (−2.82; 95% CI, 0.44 to −6.09) compared with MSPI, which was not statistically significant. As expected, T1 outcome values were significant T2 outcome predictors.

Regression analysis to evaluate the effect of interproximal reduction (IPR) on the final overbite in the Invisalign group revealed that only maxillary IPR was significantly associated with overbite at T2 in this group (b = 0.45; 95% CI, 0.02-0.87) with mandibular IPR inducing a nonsignificant effect (b = −0.15; 95% CI, −0.32 to 0.02).

Regression modelling for the post-treatment overbite

The final overbite differed between treatment arms; however, this difference was mainly between male patients (Fig 2).

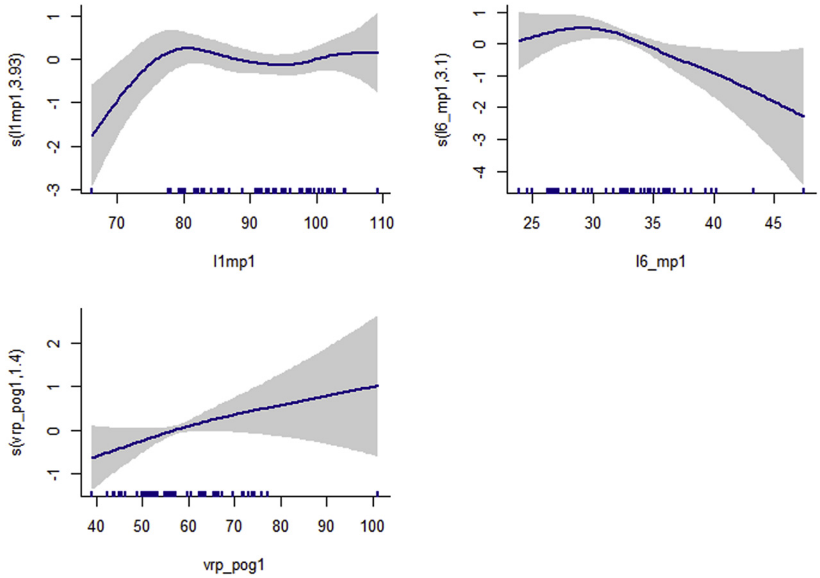

Fig 3. Plots of L1-Mp, L6-MP, and VRP-Pog at T1 vs T2 overbite fit as smooth nonlinear functions in GAM.

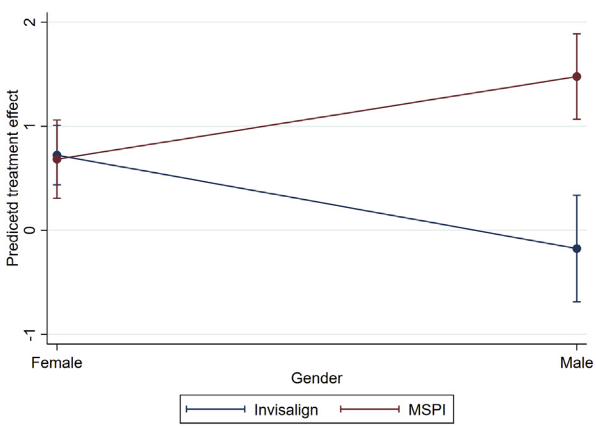

Fig 4. Interaction plot for treatment × gender.

Significant T1 predictors for final overbite using stepwise backward elimination, manual variable selection, and the GAM approach are shown in Table IV. Among the 3 models, the GAM has the best fit statistics as indicated by the AIC, deviance, and *F* test from analysis of variance. The smooth plots from the GAM show nonlinearity for the nonparametric part of the model, supported by the approximate *P* values for the smooth terms (Table IV; Fig 3). In all 3 models, there was strong evidence of interaction between treatment × gender, suggesting that the effect of treatments on T2 overbite is not the same across gender. Gender stratified treatment effect based on the stepwise model was not-significant for females (−0.04, 95% CI, −0.52 to 0.44; $P = 0.87$) and highly significant for males (1.65; 95% CI, 0.99 to 2.32; $P < 0.001$) showing, a 1.65 mm greater improvement in the final overbite in males using MSPI compared with the Invisalign group (Fig 4). The GAM diagnostic plots show a reasonable fit (Fig 5).

The relative influence of the T1 value of each cephalometric variable and treatment and gender on the T2 overbite from the GBM approach is illustrated in Figure 6. In contrast, Figure 7 depicts the average and the individual conditional expectation of the final overbite at T2 as a function of the T1 overbite. The variability in the expectation is evident. In the configuration of the selected model, after using a grid with 81 parameter combinations, shrinkage was 0.01, the minimum number of observations in the terminal nodes of the trees was 3, and the interaction depth was 5. The minimum root mean square error for this model was achieved with 245 iterations, and it was 0.86, indicating that the predicted value compared with the true overbite value at T2 differed by 0.86 mm. This deviation may be considered large but not unexpected given the small sample size. All 4 models (stepwise backward elimination, manual variable selection, GAM, and GBM) showed some variability in the selected predictors for the final overbite. However, all models selected T1 overbite and type of treatment as key predictors for a final overbite. This increases our confidence in the identified association between those variables and T2 overbite.

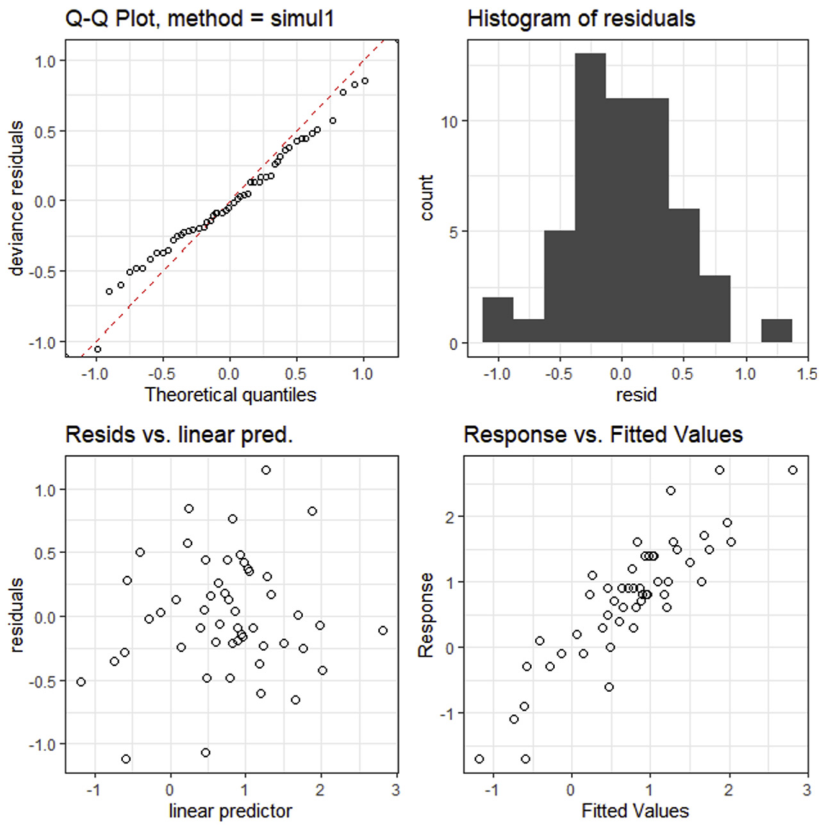

Fig 5. GAM diagnostic plots.

DISCUSSION

Key results and interpretation

This study examined the vertical and sagittal dentoskeletal effects of 2 independent treatment approaches in an adult open bite population. Although previous studies have looked at Invisalign[16-19] or MSPI[5,10,12] alone, to our knowledge, this is the first direct comparison of these 2 approaches. The relevance of such a comparison is founded on anecdotal evidence,[14] case reports,[14,15] and a recent retrospective study,[18] which suggested that Invisalign may partly achieve open bite closure via an intrusive posterior bite-block effect. In that case, the treatment effects of Invisalign may be somewhat analogous to those repeatedly demonstrated using orthodontic miniplates or miniscrews.[5-7,9,11-13,31-33] The results obtained in our study indicate that the mechanisms underlying overbite correction for each examined treatment modality are different.

In patients with an open bite, it stands to reason that obtaining a satisfactory positive overbite is a primary metric of treatment success. In line with previous research, both appliances effectively improved the overbite relationship in all included patients.[5,10,12,16-19] In the present study, the T1 open bite was on average 0.85 mm greater in the MSPI group than in the Invisalign group—perhaps reflecting clinician preference in selecting a treatment approach on the basis of the severity of the open bite. There was evidence that MSPI was more effective in overbite improvement in male vs female patients compared with Invisalign, whereas there was almost no difference across gender when treated with MSPI. For 3 patients (12.5%) in the MSPI group and 5 patients (17.2%) in the Invisalign group, a small residual open bite was present after treatment.

Our study corroborates findings that MSPI results in molar intrusion. Posterior intrusion values in the range of 2.3-3.6 mm for the maxillary molars[5,10,12] and 1.3 mm[5] for the mandibular molars have been reported in primarily adult patients with open bite treated with MSPI. Consistent with previous studies, we reported an intrusion of approximately 1.8 mm for maxillary molars and 0.7 mm for mandibular molars demonstrating less intrusion of the mandibular molars than the maxillary molars. Root morphology and the structural profile of the alveolar housing and cortical bone make molar intrusion more

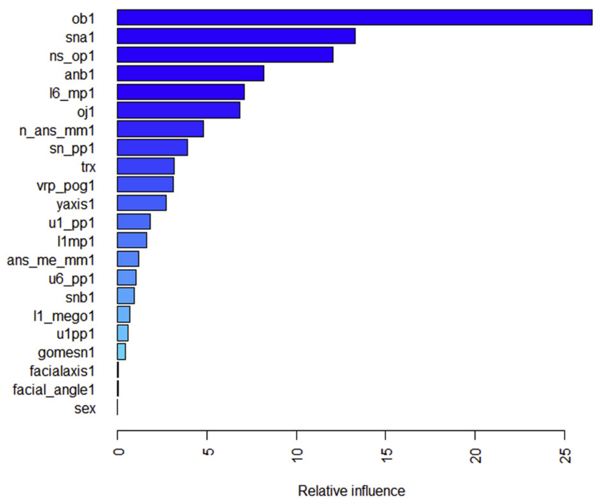

Fig 6. Bar plot of the relative influence of each variable on the final overbite using GBM.

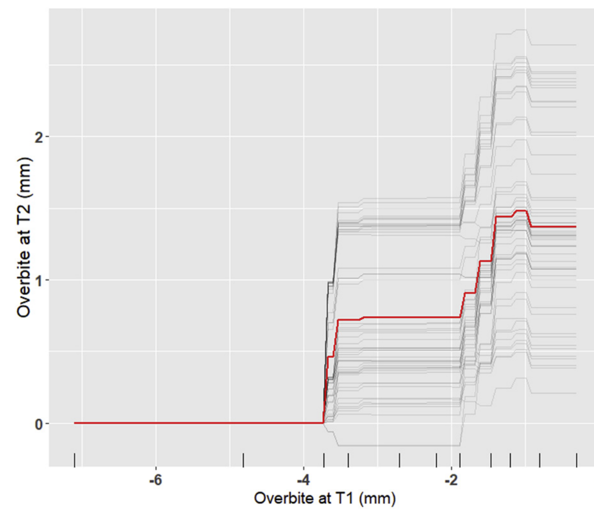

Fig 7. Individual conditional expectation plot for overbite at T2 vs overbite at T1 from GBM. The *red* shows the average expected change in the overbite at T2 vs the overbite at T1, and the *gray* show the individual patient predictions.

difficult in the mandible than the maxilla,[34] which is reflected in our results. However, the molar intrusion in our study was less than previously reported. At T1, the open bite for all but one[10] of the studies mentioned was greater than our sample as we included both patients with mild and severe open bite. Therefore, the discrepancy in the maxillary molar intrusion may reflect the reduced need for the posterior intrusion to correct the less severe open bite observed in our sample.

Secondary to molar intrusion, we found a reduction in MP angle (2.2°) and lower ANS-Me (2.9 mm) achieved with MSPI, which is a clinically important finding, similar to values previously reported.[5,10,12] The 3 mm improvement in the horizontal projection of pogonion, the concurrent 1.5° reduction in ANB, and the decrease of the lower face height and MP angle observed in our sample could provide evidence for recommending MSPI as a potentially suitable option in nongrowing patients with borderline surgical-orthognathic skeletal hyperdivergent Class II malocclusion.[5,33]

Invisalign did not deliver any intrusion to maxillary and mandibular molars, and consequently, there was no forward mandibular autorotation. These findings are in accordance with 2 recent cephalometric case series studies.[16,17] A separate study reported approximately 0.6 mm of mandibular molar intrusion, with a 0.9° reduction in MP angle and a 1.5 mm reduction in lower ANS-Me.[18] Finally, a fourth study found <0.5 mm of maxillary and mandibular molar intrusion, with a 0.73° reduction in MP angle and a 1.17 mm reduction in ANS-Me.[19] Despite the reported statistically significant associations, the clinical significance of the observed changes is questionable. In addition, assessment of potential biases and confounders was not possible as 1 sample was retrospectively drawn at random from 3 private orthodontic practices with no further details,[18] and the other[19] included patients preceding Align's G4 algorithms for open bite treatment.

In the present study, incisor inclination remained relatively stable in the MSPI group. Maxillary incisors in the MSPI group were 2.82° (95% CI, −0.44 to 6.09) more proclined than in the Invisalign group at T2, a nonstatistically significant finding. This difference between treatments may be explained by the vertical control provided by anchorage from the miniplates. As such, the vertical position and torque of the incisors could be titrated in accordance with the specific needs of the patient. Many patients with skeletal open bite present with an excessive maxillary gingival display.[2,3,35] Thus, from both an esthetic and stability standpoint, extruding the incisors beyond 1-2 mm rarely constitutes a treatment objective.[13]

The difference in overbite correction across our MSPI and Invisalign groups appears to stem also from differences in the extrusion of the maxillary and mandibular incisors. The distance of the incisal edges of the maxillary and mandibular incisors to the palatal plane increased by 1.05 mm and 0.9 mm in Invisalign compared with MSPI. However, maxillary incisor extrusion could be confounded by the accompanied 6° retroclination, a movement that geometrically brings the incisors into a more occlusal position. The amount of retroclination of the maxillary incisors noted in our study is almost identical to that reported by Garnett et al.[16] In contrast, other studies have not assessed changes in incisor angulation relative to their apical base. Mean extrusion of the maxillary and mandibular incisors has been previously reported to range between 0.5 and 1.5 mm.[16-19] Those findings agree with our results showing mean extrusion of 1 mm without changes of mandibular incisor inclination relative to the MP. Open bite at T1 in the Invisalign group was 2.2 mm, which is more severe than previously reported. However, the observed vertical displacement of incisal edges in this study is consistent with previous studies. In addition, we found a significant association between maxillary IPR and overbite at T2. It is plausible that the space obtained through IPR was used to tip the maxillary incisors palatally and contribute to the overbite improvement. However, this association should be interpreted cautiously, as IPR could have been used for other purposes (eg, relief of crowding). Similarly, space for retroclination may have already been available or obtained through transverse arch expansion.

Fixed appliances inherently open the bite, and these sequelae of posterior extrusion in patients with an open bite are often undesirable.[34,36] In this study, Invisalign appeared to confer vertical control but could not substantiate claims of a clinically or statistically significant posterior bite-block effect. Bonded passive acrylic bite-block of 5-10 mm thickness has demonstrated effectiveness in obtaining modest posterior intrusion and a forward mandibular rotation in growing patients.[37] Invisalign aligners have a thickness of 0.76 mm.[38] Whether 1.52 mm of interocclusal aligner material is sufficient to exceed the freeway space and stretch the sarcomeres of the masticatory musculature to deliver an intrusive force is questionable. It is usually recommended that patients remove the aligners during eating, and hence the contribution of masticatory forces is likely to be negligible or nonexistent during aligner wear. Skeletal hyperdivergent facial pattern has been associated with reduced maximum bite force and reduced electromyographic activity and muscle efficiency.[39-42] Thus, questioning the ability of those patients to deliver occlusal forces of sufficient magnitude and duration to accomplish appreciable intrusion. From our results and those obtained in other studies,[16-18] it appears unlikely that the occlusal coverage of the aligners combined with intermittent occlusal forces could induce sufficient molar intrusion that can result in mandibular autorotation and anteroposterior correction. As the anterior teeth are extruded with the assistance of bonded attachments, a reciprocal intrusive force is designed to be directed to the posterior teeth. Indeed, this forms the biomechanical basis for Invisalign's G4 algorithm, introduced in 2011 for open bite treatment.[28] The reliability of the designed force system to deliver the prescribed movements is not confirmed by the available evidence.[43] In agreement to other studies,[16-19] our study demonstrated that incisor movement was the primary mechanism of open bite closure. Therefore, it appears reasonable to consider Invisalign for adult patients with an open bite in which vertical maintenance of posterior teeth is desired and incisor extrusion is not contraindicated.

Limitations

The limitations pertinent to cephalometric analysis are well documented, and these were the primary limitations in this study. Inconsistent head position, movement during exposure, and exposure settings may all variably contribute to measurement inaccuracy.[44,45] A single investigator (B.P.S.) sequentially localized landmarks using Dolphin digital tracing software to minimize landmark identification error.[46,47] The error for measurements obtained in this study was quite low.

The magnitude of the open bite at T1 is a critical determinant of the potential for significant vertical and horizontal dental changes during treatment. This is also reflected in all exploratory analyses applied in the present study. The lack of consistency among the implemented models in identifying influential cephalometric variables at T1 for final overbite prediction highlights the limitations of using T1 cephalometric variables for such a task, including intercorrelations of the cephalometric measurements, thin data, and statistical methods.[48-51] Nevertheless, all 4 models showed agreement in identifying T1 overbite as a common determinant of T2 overbite. There was evidence that Invisalign and MSPI had the same effect in females in terms of overbite improvement, whereas in males, Invisalign was less effective. This discrepancy may be attributed to different compliance patterns across gender. Evidence regarding patient cooperation with removable orthodontic appliances indicated that males were less compliant with appliance wear.[52] Although existing evidence of adherence to treatment in orthodontics mainly applies to children and adolescents, adult males were less likely to be compliant even when suffering from other significant medical conditions.[53]

Premature anterior occlusal contacts may limit the expression of mandibular autorotation. In the Invisalign system, the staging of incisor movements should be carefully planned to avoid unwanted lingual tipping and incisor extrusion early in the treatment sequence. In our study, ClinCheck approval was based on a patient-by-patient scenario without a standardized protocol for movement sequencing among clinicians.

As emphasized in a recent article,[54] there is considerable debate on attachment design, tooth movement sequencing, and the extent of overengineering required in ClinCheck for specific clinical scenarios. In the present study, all clinicians used attachments on almost all teeth; however, total dimensions, beveling, and composite material used for their construction differed. This could have introduced additional confounders pertinent to attachment number, size, design, and composite resin material properties.

In the MSPI group, SARME was performed as an adjunctive procedure in 4 patients, and this may have increased the amount of intrusion via the regional acceleratory phenomenon effect[55] as intrusion may have occurred at 2 distinct interfaces—the dental socket and the osteotomy zone. Although corticotomy-assisted intrusion has been studied,[56] future research evaluating the effect of SARME on the rate and magnitude of intrusion would be essential.

Treatment mechanics such as distalization, extraction space closure, or the use of intermaxillary elastics may cause bite opening. To control for this, patients who had extractions or more than a half unit of anteroposterior correction were excluded from the study. Finally, open bite malocclusions are highly prone to relapse.[57] Although the stability of MSPI has been assessed up to 4-years posttreatment,[12] the stability of Invisalign is unclear. Therefore, long-term follow-up of both treatment approaches would be useful to ascertain their relative stability and inform recommendations for overcorrection and retention strategies.

Another limitation of the present study could be its retrospective design; however, to minimize potential selection bias, treating clinicians provided the investigators with access to their Invisalign accounts and were not involved at any stage during patient selection, data collection, and analyses. Similarly, patients in the skeletal plates group were retrieved by practice managers who allowed full access to patient lists and records. Patients that qualified for inclusion but contained records of poor quality or incomplete or missing information were not included. Nine patients from the MSPI group and 8 from the Invisalign group were excluded on this basis, which further limited our sample. The most common reason for exclusion was missing T1 and T2 lateral cephalograms, implying random missingness.

Until further evidence emerges, it is difficult to evaluate the generalizability of our results and those obtained in similar studies to a broader open bite population and other aligner systems; however, our sample corresponds to a usual practice setting while impartially acknowledging potential biases, confounders and limitations could improve transparency and inform design and conduct of future studies.[58]

Generalizability (external validity) of the study results

The results of this study are expected to apply to adult patients with AOB and characteristics described in our inclusion and exclusion criteria. Clinician experience with skeletal plates and Invisalign and patient compliance are likely to be important determinants for the applicability of our findings.

CONCLUSIONS

Both MSPI and Invisalign effectively increase the overbite in adult open bite patients. MSPI delivered significant molar intrusion and a forward counterclockwise mandibular rotation, whereas the position of the incisors was maintained. Invisalign accomplished open bite closure primarily through maxillary incisor relative extrusion by palatal tipping and mandibular incisor extrusion without inducing any other clinically appreciable skeletal and dental effects.

AUTHOR CREDIT STATEMENT

Brett Peter Steele contributed to conceptualization, methodology, validation, investigation, and original draft preparation; Nikolaos Pandis contributed to conceptualization, methodology, formal analysis, data curation, and manuscript review and editing; M. Ali Darendeliler contributed to conceptualization, methodology, resources, and manuscript review and editing; Alexandra K. Papadopoulou contributed to conceptualization, methodology, validation, data curation, manuscript review and editing, supervision, and project administration.

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SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ajodo.2021.03.022.

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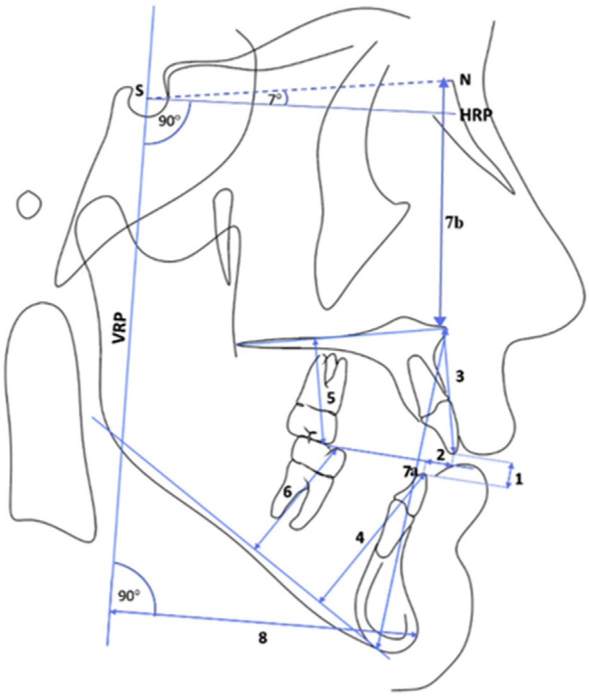
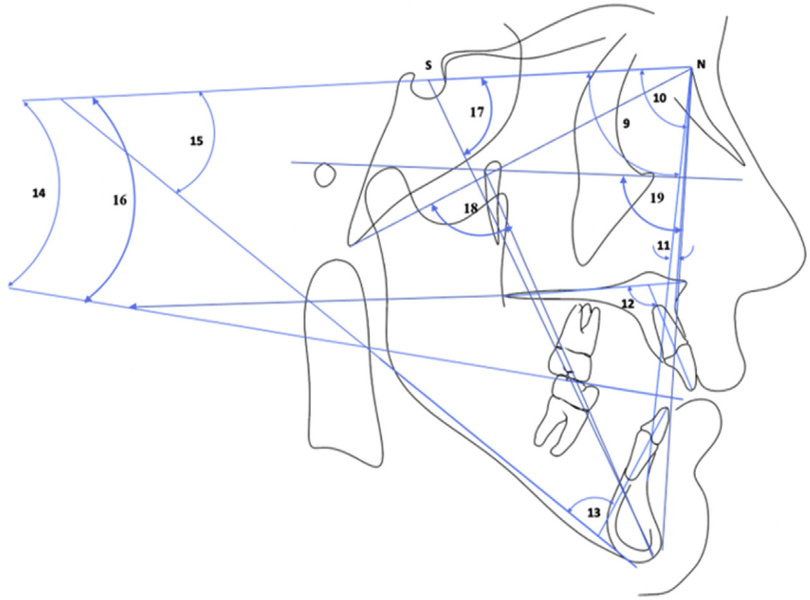
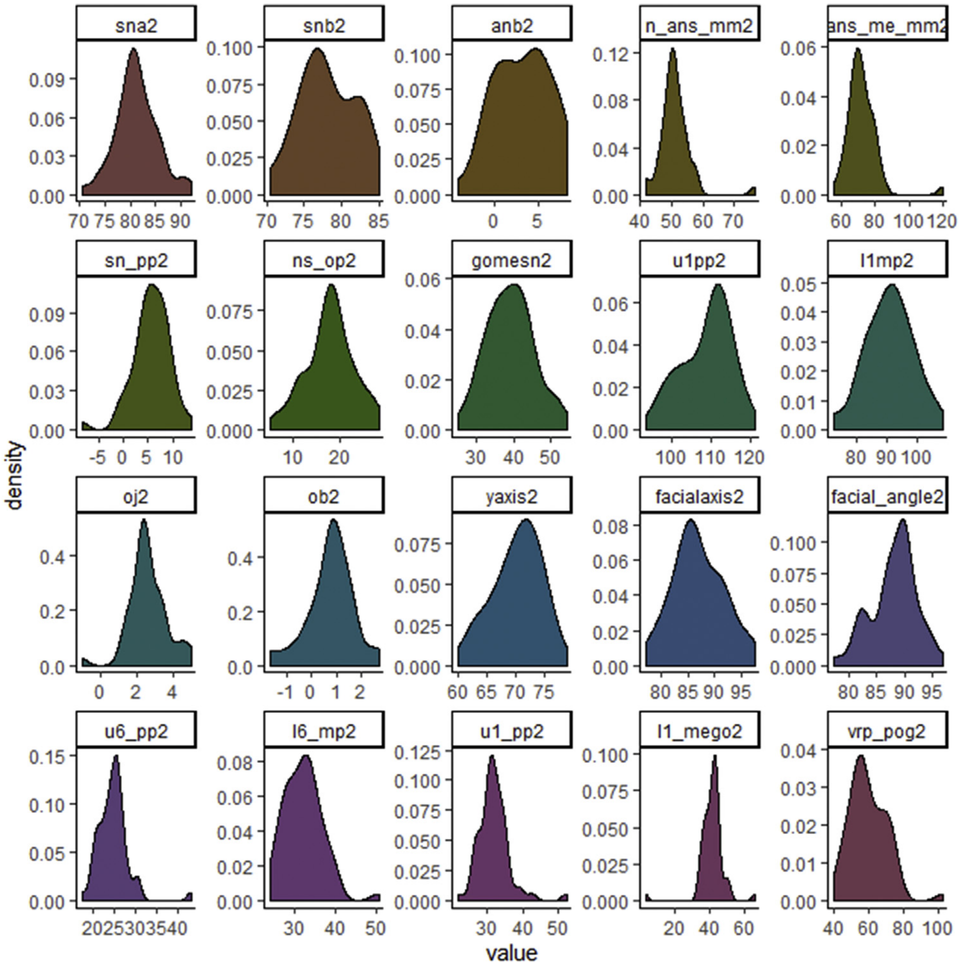


Supplementary Fig 1. Linear cephalometric measurements. *1,* Overbite (OB); *2,* Overjet (OJ); *3,* Perpendicular distance of maxillary incisal edge to palatal plane (PP-U1); *4,* Perpendicular distance of mandibular incisal edge to mandibular plane (Mp-L1); *5,* Perpendicular distance of maxillary first molar mesial cusp tip to palatal plane (PP-U6); *6,* Perpendicular distance of mandibular first molar mesial cusp tip to mandibular plane (L6-MP); *7a,* Lower anterior face height (ANS-Me); *7b,* Upper anterior face height; *8,* Perpendicular distance of point pogonion to the vertical reference plane (VRL-Pog).



Supplementary Fig 2. Angular cephalometric measurements. *9*, SNA; *10*, SNB; *11*, ANB; *12*, Angle between maxillary incisor long axis to palatal plane (U1-PP); *13*, Angle between mandibular incisor long axis to mandibular plane (L1-Mp); *14*, Occlusal plane angle (SN-OP); *15*, Mandibular plane angle (Mp-SN); *16*, Palatal plane angle; *17*, Y-axis; *18*, Facial axis; *19*, Facial angle.



Supplementary Fig 3. Distribution of cephalometric variables at T2.

Supplementary Table. Definitions of the cephalometric measurements

Measurement	*Definition*
Vertical parameters	
N-ANS, mm	Upper anterior face height: Linear distance between point N and anterior nasal spine (ANS)
ANS-Me, mm	Lower anterior face height: Linear distance between ANS and Menton point
SN-PP, °	Maxillary plane angle: Angle between SN and ANS- posterior nasal spine (PNS) line
SN-Go-Me, °	MP angle: Angle between SN and Gonion-Menton (Go-Me) line
SN-OP, °	OP angle: Angle between SN and OP
Y-axis, °	Anterior angle formed between SN and Sella-Gnathion line
Facial axis, °	Posterior angle formed between Nasion-Basion line and Ptm-Gnathion line
OB, mm	Overbite: Vertical linear distance between maxillary incisor (U1) and the mandibular incisor (L1) tips taken perpendicular to the OP
Sagittal parameters	
SNA, °	SN-A point angle
SNB, °	SN-B point angle
ANB, °	A point-Nasion-B point angle
Facial angle, °	Posterior angle formed between Frankfort Horizontal and Nasion-Pogonion line
VRP-Pog, mm	Linear perpendicular distance from point Pogonion to the vertical reference plane
OJ, mm	Overjet: Linear distance between the maxillary incisor (U1) and the mandibular incisor (L1) tips taken parallel to the OP
Molar position	
PP-U6, mm	Perpendicular distance of the mesial cusp tip of the maxillary first permanent molar (U6) to the palatal plane ANS-PNS; line passing from the points ANS and PNS
L6-MP, mm	Perpendicular distance of the mesial cusp tip of the mandibular first permanent molar (L6) to the MP (Go-Me)
Incisor position	
PP-U1, mm	Perpendicular distance of the maxillary incisor (U1) tip to the palatal plane (ANS-PNS)
U1-PP °	Angle between the long axis of the maxillary incisor (U1) tip and the palatal plane (ANS-PNS)
Mp-L1, mm	Perpendicular distance of the mandibular incisor tip (L1) to the MP (Go-Me)
L1-Mp, °	Angle between the long axis of the mandibular incisor tip (L1) and the MP (Go-Me)

Ptm, most superior and posterior point of the pterygomaxillary fissure.