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Measurement of orthodontic tooth movement in lower anterior teeth by means of magnetic resonance imaging–a prospective pilot study

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Abstract

Background During orthodontic treatment, the risk of gingival recession may increase, especially in the mandibular anterior region due to thin alveolar bone. This prospective pilot study aimed to develop a standardized evaluation method based on magnetic resonance imaging (MRI) for analysing tooth movements and tissue dimensions and to investigate the impact on periodontal parameters during orthodontic levelling.

Materials and methods Participants aged 12 to 18 with lower jaw crowding underwent MRI scans before (T0) and five months into orthodontic treatment (T1). The following tissue dimensions were analysed: thickness of free and supracrestal gingiva (FGT, SGT), thickness of buccal alveolar bone (ABT) at three measurement levels (ABT2, ABT4, ABT8), and gingiva and alveolar bone height (GH, ABH). Additionally, tooth positions (apex position and tooth axis inclination) were determined.

Results Ten patients (60% female, 40% male) aged 14.33 ± 1.35 years were included after the exclusion of 3 datasets due to motion artefacts. MRI measurements showed significant changes in tooth inclination ($2.93 \pm 4.77°$, $p < 0.001$), bucco-lingual apex position (-0.45 ± 1.03 mm, $p = 0.006$), SGT (-0.07 ± 0.19 mm, $p = 0.020$), ABT8 (0.42 ± 0.59 mm, $p < 0.001$), ABH (-0.29 ± 0.68 mm, $p = 0.006$) and GH (0.31 ± 0.9 mm, $p = 0.030$) between T0 and T1. Inclination changes correlated negatively with FGT ($R = -0.422$, $p < 0.001$) and positively with ABT8 ($R = 0.404$, $p = 0.032$). Furthermore, ABT8 correlated negatively with buccal apex movement ($R = -0.392$, $p = 0.042$). Intra- and interclass correlation coefficients were excellent (0.988 and 0.975).

Conclusion Periodontal tissue changes correlated with tooth inclination or apex position changes due to orthodontic treatment. The pilot study has demonstrated the feasibility of dental MRI as a radiation-free alternative to cone-beam computed tomography for monitoring orthodontic treatment. However, the methodology was susceptible to motion artefacts.

Trial registration ISRCTN, ISRCTN12689212. Registered 11 April 2024 Retrospectively registered, http//www.isrctn.com/ISRCTN12689212.

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Keywords Dental MRI, Orthodontic tooth movement, Gingiva thickness, Alveolar bone thickness, Lower anterior teeth

Introduction

Orthodontic therapy is usually initiated with the so-called levelling and alignment phase. Highly elastic levelling archwires are employed to level-out the teeth's horizontal, vertical, and rotational positional discrepancies. The archwire geometry of a straight superelastic levelling wire appears to be very simple, however, highly complex and statically non-determined multi-tooth mechanics come into effect after insertion of such a wire [1]. Force systems acting on individual teeth depend not only on the material properties, but also on tooth malalignments to a large extent, i.e. on the discrepancy between bracket slot and archwire, as well as on frictional forces between wire, bracket, and ligature. This, in consequence, may lead to unwanted proclination of the anterior teeth. It has been observed that such tooth movements result in increased incidence of dehiscence and fenestration formation in cases with thin phenotype [2].

Since superelastic nickel-titanium (NiTi) archwires exhibit a non-linear deformation mode also characterized by pronounced hysteresis between loading and unloading, their behaviour does not correspond to Hooke's law [3]. As a consequence of these unusual properties and the complex multi-tooth geometry which becomes even more complicated because of the frictional effects, one cannot assess the mechanical behaviour of a fully-ligated NiTi levelling archwire by simple analytical methods such as consecutive two-tooth models [4]. Both laboratory studies and a finite element analyses cannot fully capture the complex in vivo situation, which includes factors like tooth-to-tooth contact, saliva, the reaction of the periodontal ligament, and intermittent occlusal forces [5, 6]. A detailed understanding of the components and their interplay within the tested object in vivo is crucial for accurately modelling an orthodontic force system [7]. Given the scarcity of investigations of in-vivo tooth movements during orthodontic treatment, especially in the lower jaw, gaining an exact understanding of tooth movements during orthodontic treatment is vital for controlling the applied forces and moments [8].

Current advancements in imaging techniques, specifically cone-beam computed tomography (CBCT), have revolutionized the assessment of tooth movement in three dimensions [9]. These three-dimensional assessments provide a more accurate and comprehensive understanding of tooth movement compared to traditional two-dimensional measurements on CBCT reconstructions. By incorporating three-dimensional assessments, orthodontists can obtain precise information about the position and angulation of teeth in relation to surrounding structures, such as alveolar bone and soft tissues. Furthermore, the use of three-dimensional evaluations allows for the detection and measurement of tooth movement in all planes, including rotations, translations, and angulations. By superimposing the CBCT datasets, the dental structures can be aligned and registered based on stable anatomical landmarks or reference points [10]. Clinically, the use of CBCTs for follow-up investigations is restricted due to concerns regarding radiation exposure, especially in adolescent orthodontic patients.

Magnetic resonance imaging (MRI) has become an important imaging modality for visualising specific pathological processes in the jaw and teeth without exposing the patient to radiation. It has been shown to be particularly useful in studying inflammatory periodontal disease [11], characterising focal periapical lesions of the teeth, and quantifying root perfusion in autograft teeth [12, 13]. MRI is useful for characterising soft tissues surrounding teeth [14] and for early detection of inflammatory or neoplastic pathologies [15]. A coil for dental MRI has been proposed to enable MRI with an improved resolution for hard tissues within clinically feasible scan times [16, 17]. This has enabled cephalometric measurements [18], high quality and even quantitative dental and oral-maxillofacial imaging studies [19], as well as routine diagnostics where soft tissue contrast or avoiding radiation dose is critical [17, 20]. Measurements obtained from MRI are highly reliable and demonstrate good to excellent agreement with CBCT [14, 18]. However, no orthodontic follow-up study has been conducted using dental MRI so far.

The main objective of this study was to establish an MRI-based protocol to clinically evaluate the three-dimensional movement of lower anterior teeth during initial orthodontic treatment by means of two consecutive MRI scans: one before treatment (T0), and another five months after start of orthodontic treatment (T1). Secondary aim was to assess the changes in gingival thickness and alveolar bone dimensions surrounding the anterior teeth during orthodontic treatment.

Material & methods

Patients

Adolescents with significant orthodontic treatment need and anterior mandibular crowding were consecutively enrolled in this prospective clinical case series. All participants were about to undergo orthodontic therapy at the Department of Orthodontics, University Clinic of Dentistry (Medical University of Vienna, Austria) between February 2022 and August 2023. Only participants aged between 12 and 18 years with a significant need for orthodontic treatment, as determined by the Index of Orthodontic Treatment Need (IOTN) [30], and mandibular anterior crowding of more than 3 mm with fully erupted permanent lower teeth were included. Exclusion criteria comprised a history of claustrophobia, previous fixed orthodontic treatment, gingival recessions, craniofacial anomalies, and medication that affects periodontal structures. The patients and caregivers provided written informed consent for the MRI examinations and for the publication of this case series, including accompanying images. The study protocol was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Medical University of Vienna (EK Nr: 1654/2021).

Study protocol

Prior to the application of the orthodontic appliance in the lower jaw, the patients underwent 3D imaging of the mandible by MRI at the Department of Radiology, University Clinic of Dentistry, Vienna. After the first MRI, the patients received preadjusted brackets (SilikonPlus™, American Orthodontics, United States) with a prescription according to McLaughlin, Bennet and Trevisi in the mandible. For molars, buccal tubes were used (Titanium, Ormco, United States). The patients underwent treatment with a standardized sequence of fully ligated archwires, which included 0.014-inch NiTi and 0.016×0.022-inch NiTi archwires (Orthonol, TigerDental, Austria). After five months, a second MRI was conducted using the same settings. No mandibular teeth were extracted during this period. The archwires and any metal ligatures were removed for MRI acquisition and later reinserted.

MRI acquisition

MRI examinations were conducted using a 3T MRI system (Magnetom Skyra, Siemens Healthcare GmbH, Germany) and a 15-channel dental coil (Mandibula coil, Noras MRI products Gmbh, Germany). The patients were examined with their lips and tongue in a resting position and a cotton gauze inserted in the anterior region of the lower vestibule without pressure for retraction of the lower lip. A PD weighted sequence with fat suppression was applied as described elsewhere [14]. The MRI scan was performed using a PD-weighted 2D sequence with a 150 mm field of view for the readout, a voxel size of 0.2/0.2/1 mm, a base resolution of 320, a slice thickness of 1.0 mm, a Repetition Time (TR) of 2920.0 ms, an Echo Time (TE) of 12ms, a 142 degrees flip angle, 46 sections, and low Specific Absorption Rate (SAR) pulse type. The time of acquisition was 5:58 min.

Measurements

Twenty canines and forty incisors were analysed in six dentogingival units for each patient. Image reconstruction and visual analysis were performed using 3D software (Mimics Innovation Suite 24.0, Materialise, Belgium). Two MRIs per patient (T1 and T0) were imported into the software and the T1 MRI was superimposed on the T0 MRI using the 'Automatic registration' and 'Transformation' tools. The mandibular plane was defined by three points: menton, left gonion, and right gonion (see Fig. 1). The 3D coordinates of these points were checked for congruence between the T0 and T1 datasets. The axis of each tooth was defined as a line connecting the apex and the most coronal part of the pulp. This was done after adapting the image reconstruction along the long axis of the tooth in all three planes (see Fig. 2). The inclination of the tooth was measured as the angle its axis and the mandibular plane. Any increase in this angle during orthodontic treatment was referred to as proclination.

Soft and hard tissue dimensions surrounding the respective tooth were measured perpendicularly to its long axis (Fig. 3), as previously described [14]. The thickness of the free gingiva (FGT) was defined as the buccal gingiva thickness 1 mm below the gingival crest. The thickness of the supracrestal gingiva (SGT) was measured 1 mm coronally of the alveolar bone crest, and the thickness of the alveolar bone (ABT) was evaluated at three different apico-coronal levels along the axis of the tooth: 2 mm (ABT2), 4 mm (ABT4), and 8 mm (ABT8) below the alveolar bone crest. Alveolar bone height (ABH) and gingival height (GH) were measured perpendicular to the mandibular plane.

To quantify the bucco-lingual displacement of the tooth apex during orthodontic treatment, a circular sketch was designed to mirror the anterior mandibular curvature extending between the canines and aligned parallel to the mandibular plane (Fig. 4a and b). Subsequently, it was exported into a second 3D software (3-matic, Materialise, Belgium). The circular sketch and the apex points from the T0 and T1 datasets were then orthogonally projected onto the mandibular plane (Fig. 4c). The Euclidean distance alteration, which spans from the circle´s centre to the apex points at T0 and T1, therefore serves as a metric for the bucco-lingual apex displacement concurrent with tooth movement.

All steps of the image reconstruction and measurement process were performed by the same examiner (M.S.), who possesses extensive experience in the dental field and dental imaging analysis. Similar to a previous study investigating intra-rater reliability on gingiva thickness measurements [14], this study investigated the reliability of hard tissue measurements: To assess intra-rater reliability, the same examiner (M.S.) remeasured the bone thickness of five patients in random order four months

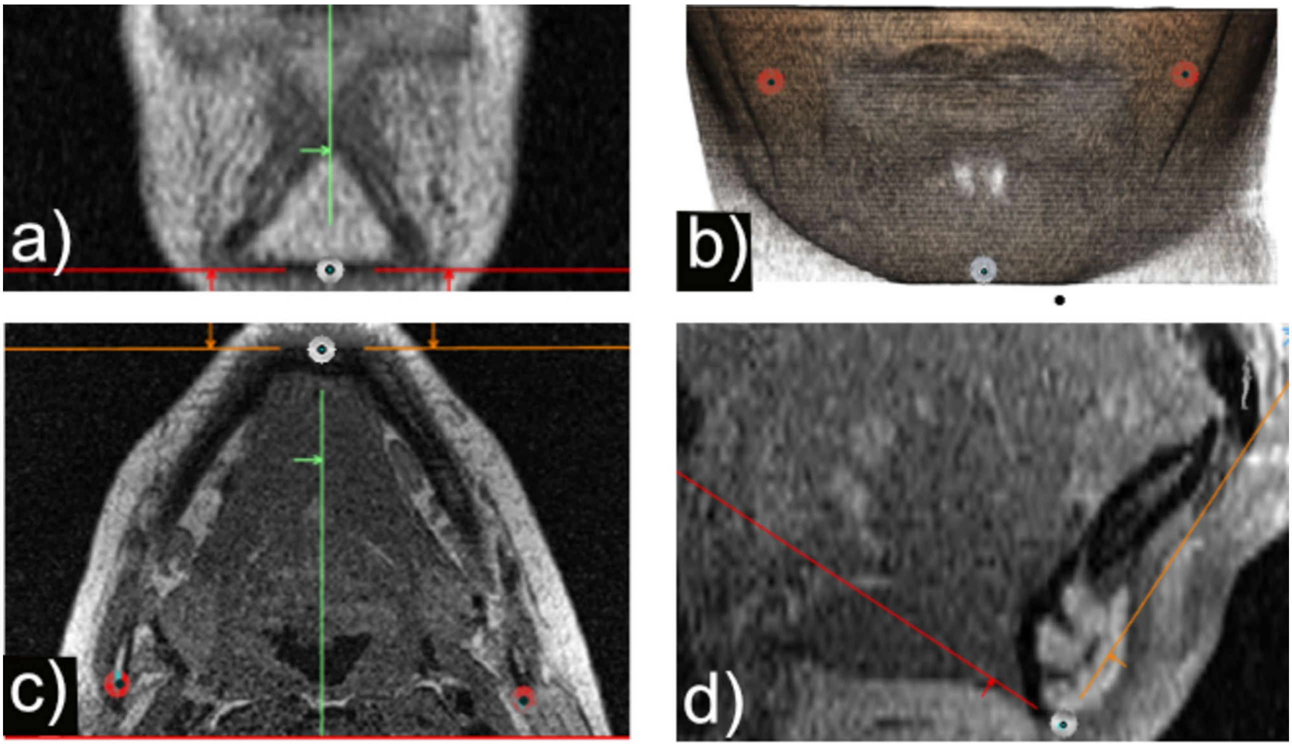

Fig. 1 Reconstructions of a representative PD-weighted MRI dataset in the software Materialise Mimics. Three points were defined to construct the mandibular plane: menton (white dot), left and right gonion (red dots) (**a**) coronal plane, (**b**) 3D reconstruction, (**c**) axial plane, (**d**) sagittal plane

after the initial measurements. To assess inter-rater reliability, the same five patients were remeasured by a second examiner (L.S.). The two observers underwent training and on one dataset that was not included in the study.

Statistical analysis

Data were assessed for normal distribution by visual inspection of histograms and by applying the Kolmogorov-Smirnov test. The groups designated SGT, ABT2, and ABT4 were found to have right-skewed distribution, requiring logarithmic for the calculation of means and standard deviations. It was not feasible to apply a logarithmic transformation to the mean values of the apex position and the mean values of the subgroups incisors and canines of Apex, FGT, SGT, ABT2 and ABT4; therefore, median and interquartile range (IQR) are presented. Analysis of the differences between T0 and T1 showed adherence to a normal distribution, allowing pairwise t-tests to be performed. Correlations between changes in tooth inclination or apex position and tissue dimensions were examined using Spearman´s correlation analysis was performed. For subgroup analysis, teeth were dichotomised into two categories based on their inclination relative to the mandibular plane at T0: (1) retroinclined teeth, characterised by an initial inclination of less than 90 degrees, and (2) proclined teeth, characterised by an initial inclination of 90 degrees or more. Furthermore, a tooth was assigned to group (3) proclination, if its inclination at T1 was greater than that at T0; conversely, if the inclination at T1 was less than that at T0, it was assigned to group (4) retroinclination. The Wilcoxon rank sum test was used to assess statistical differences between subgroups 1 vs. 2 and 3 vs. 4. P-values of less than 0.05 were considered statistically significant. All statistical tests were performed using SPSS version 29 software (IBM Corporation, United States).

Results

Thirteen patients were considered eligible for study inclusion. Three datasets had to be excluded because of motion artefacts either at T0 or T1. The remaining ten patients (60% female, 40% male) had a mean age of 14.33 ± 1.35 years.

Reliabilty

Normality assumption was not violated for any of the differences between the repeated measurements. The Bland-Altman plots comparing repeated measurements acquired on MRI datasets are displayed in Fig. 5. Figure 5a illustrates the difference between the two repeated measurements by the same examiner (M.S.), Fig. 5b describes the difference between the measurements of two different examiners (L.S. and M.S.). The

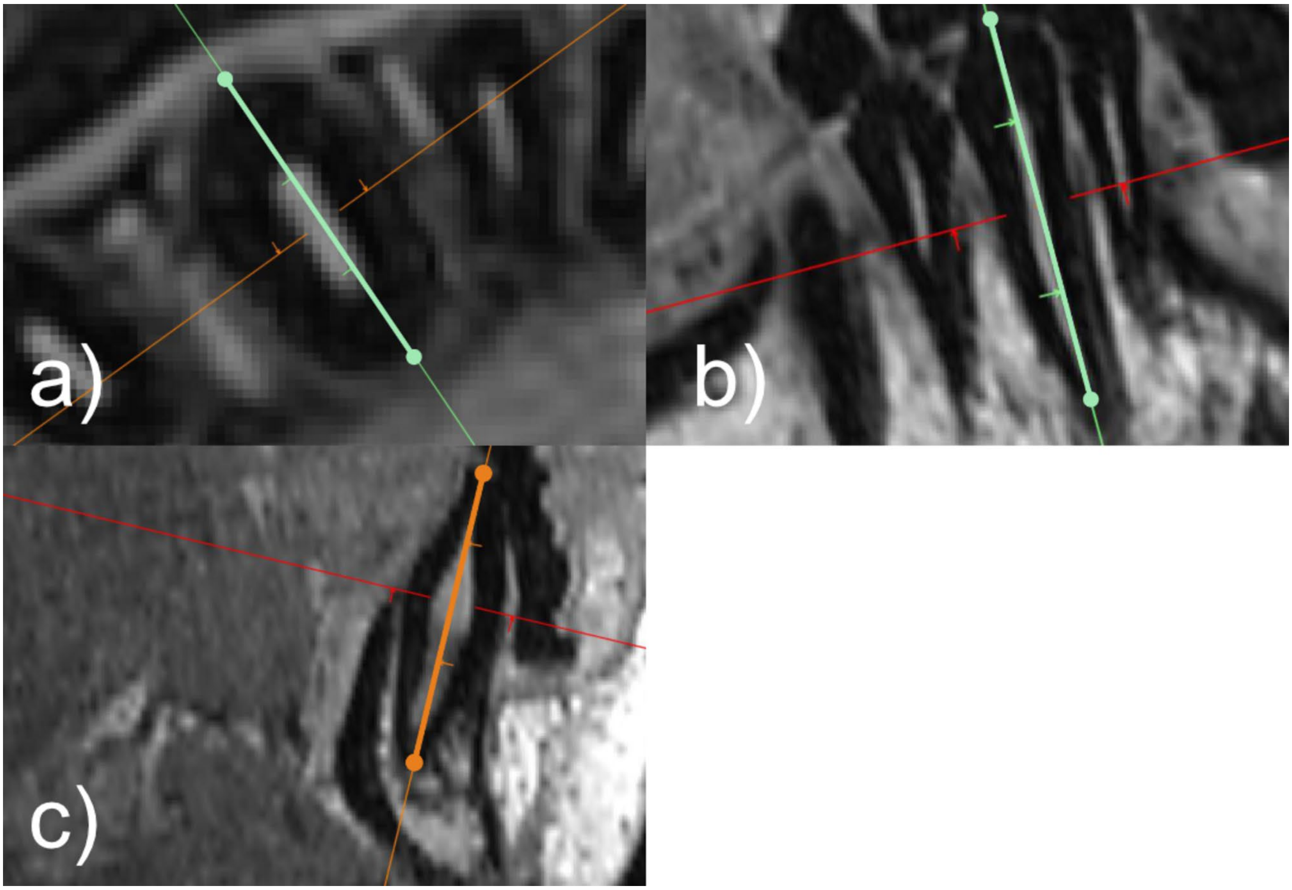

Fig. 2 3D rotation of the planes to match the long axis of the tooth for the measurements on MRI images: **(a)** axial view, rotation of the sagittal plane (green line) to divide the tooth into two equally sized halves, **(b)** coronal view, rotation of the sagittal plane (green line) to intersect with the middle of the crown and the tooth apex, **(c)** sagittal view, rotation of the coronal plane (orange line) to intersect with the crown tip and the tooth apex. The axial plane (red line) intersects with the alveolar bone crest

mean difference in repeated measurements by the same examiner was 0.03 mm, with the 95% limits of agreement ranging from −0.20 mm to 0.25 mm. The mean difference between repeated measurements by different examiners was 0.01 mm (Fig. 5b). The 95% limits of agreement ranged from −0.47 mm to 0.46 mm.

The results of the paired t-tests for bias assessment for repeated MRI measurements and corresponding ICC values are reported in Table 1. There was a statistically significant difference between the repeated measurements on the MRI. The first set of measurements was significantly higher compared with the second one, with a bias of 0.026 mm, 95% CI = 0.002–0.050, p-value = 0.035). There was no statistically difference between measurements of the two observers. ICC yielded an inter-rater agreement of 0.975 and an intra-rater agreement of 0.988 (Table 1). Thus, an excellent inter-, and intra-rater reliability could be concluded.

Tooth movement

At baseline, the anterior teeth had an average inclination of 91.63 ± 8.76 degrees. After 5 months of orthodontic treatment, the inclination increased to 94.56 ± 7.88 degrees (Table 2), with a mean difference of 2.93 ± 4.77 degrees ($p < 0.001$). The apex moved lingually by 0.45 ± 1.03 mm ($p = 0.006$). FGT did not change significantly between T0 and T1, measuring 0.71 ± 0.22 mm and 0.74 ± 0.17 mm, respectively ($p = 0.334$). However, the thickness of the supracrestal gingiva decreased significantly after 5 months of treatment, from 0.85 ± 0.75 mm at T0 to 0.80 ± 0.77 mm at T1 ($p = 0.020$). ABT did not change significantly at the measurements 2 mm and 4 mm apically from the alveolar crest, with a mean difference of 0.02 mm and 0.06 mm between T0 and T1. However, ABT8 increased after 5 months of treatment, from 1.55 ± 0.73 mm at T0 to 1.95 ± 0.91 mm at T1, with a mean difference of 0.42 ± 0.59 mm ($p < 0.001$). During treatment, ABH decreased and GH increased, resulting in a reduction of bone of 0.29 ± 0.68 mm ($p = 0.006$) and an increase in gingiva of 0.31 ± 0.90 mm ($p = 0.030$).

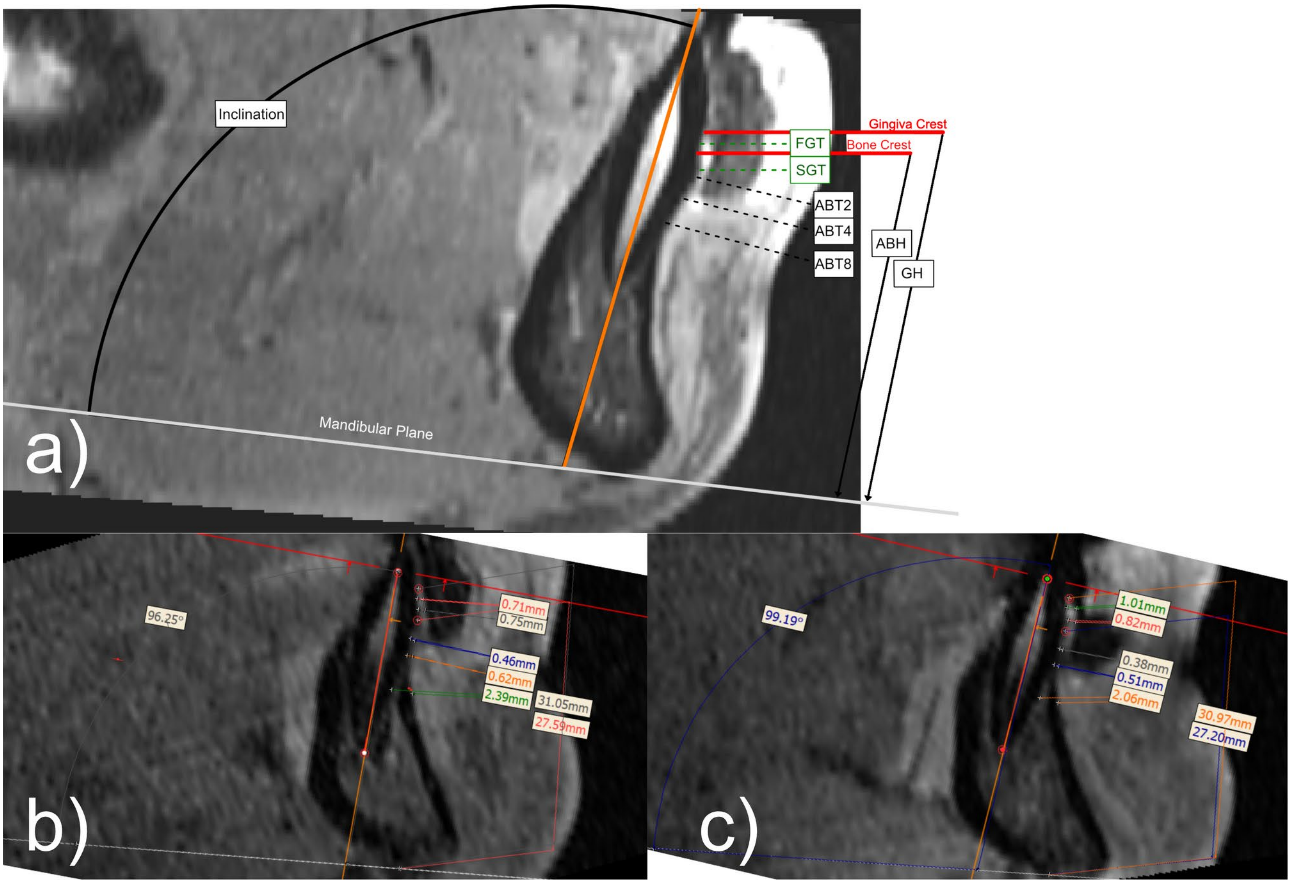

Fig. 3 Measurement sites. **a)**: Overview and visualization of the measurement sites displayed on a sagittal MRI reconstruction slice. **b)** Representative example of the measurements of a lower incisor at T0, conducted in Materialise Mimics. **c)** Representative example of the measurements of the same incisor at T1, conducted in Materialise Mimics. Abbreviations: FGT, free gingiva thickness; SGT, supracrestal gingiva thickness; ABT2, alveolar bone thickness 2 mm below the alveolar crest; ABT4, alveolar bone thickness 4 mm below the alveolar crest; ABT8, alveolar bone thickness 8 mm below the alveolar crest; ABH, alveolar bone height; GH, gingiva height

The subgroup analysis revealed a significant proclination of incisors of 3.83 ± 4.74 degrees ($p < 0.001$) and a lingual movement of the apex of 0.61 ± 0.93 mm ($p < 0.001$) after five months of levelling and aligning (Table 2). Meanwhile, the bone thickness at ABT8 was increased significantly around incisors by 0.52 ± 0.64 mm ($p < 0.001$), while the alveolar bone height decreased by an average of -0.37 ± 0.55 mm ($p < 0.001$). In comparison, canines experienced a lesser degree of proclination of 1.13 ± 4.41 degrees ($p = 1.00$) and only a slight mean apex movement of 0.14 ± 1.17 mm ($p = 1.00$). The alveolar bone height decreased only slightly by 0.14 ± 0.87 mm, which was not statistically significant.

An inverse correlation between changes in tooth inclination during orthodontic treatment (R= -0.422, $p < 0.001$) and free gingiva thickness was found. The correlation was confirmed for incisors (R= -0.68, $p < 0.001$), but not for canines ($R = 0.245$, $p = 1$). Changes in tooth inclination did not affect the parameters SGT, ABT8, and ABT4 and GH (see Table 3). However, ABT8 increased with increasing tooth inclination ($R = 0.404$, $p = 0.032$). The correlation was significant only for canines ($R = 0.700$, $p < 0.001$). ABH around the incisors decreased as the tooth inclination increased (R= -0.574, $p < 0.001$), however, this was not observed around the canines (R=-0.495, $p = 0.39$).

The correlation between the direction of apex movement and the change in tooth inclination was negative, (R= -0.454, $p < 0.001$), indicating that the apex tended to move lingually during a buccally directed change in tooth inclination. This correlation was particularly strong for canines (R= -0.600, $p = 0.005$). However, despite this observed correlation, apex displacement had a less significant effect on tissue dimensions compared to tooth inclination (Table 4). The correlation between apex movement and a decrease in bone thickness 8 mm below the alveolar bone crest (R= -0.392, $p = 0.042$) indicates that buccal displacement of the tooth apex is linked to reduced bone thickness at ABT8.

Teeth with an initial inclination of less than 90 degrees experienced an increase in inclination of 4.34 ± 1.38 degrees during initial orthodontic treatment (Table 5) and

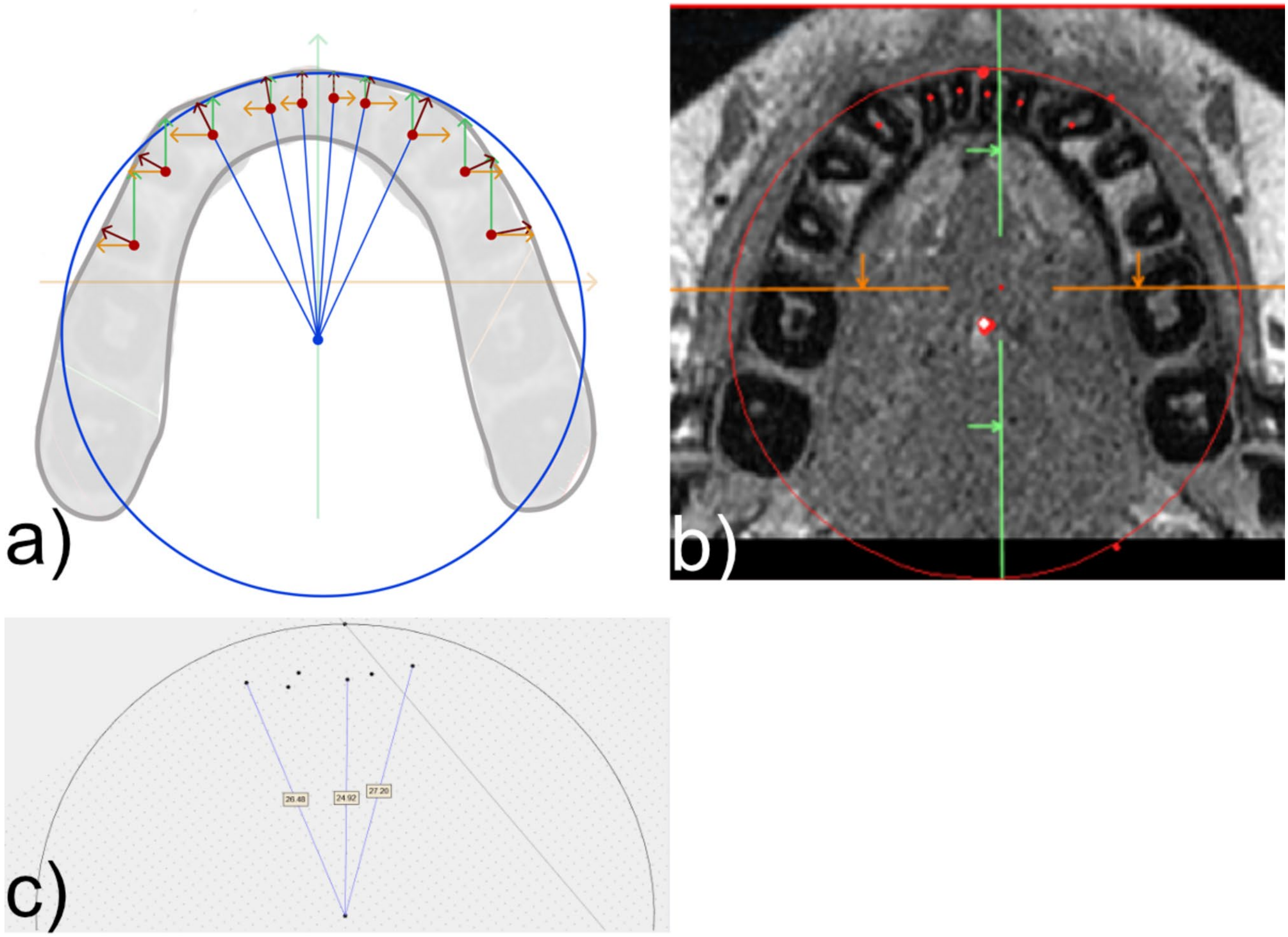

Fig. 4 Measurement method for assessing bucco-lingual apex movements during orthodontic treatment. **(a)** Schematic illustration of the measurement method: The tooth apices are represented by red dots. These dots were constructed from MRI datasets and then projected onto the mandibular plane. The hypothetical movements of the apex along the x- and y-plane are illustrated by yellow and green arrows, respectively. The bucco-lingual movements of the apices are illustrated by red arrows. The blue circle follows the anterior curvature of the mandible, with the blue dot indicating the centre of the circle. **(b)** Step 1: Construction of a circle following the anterior curvature of the mandible and definition of the tooth apices, represented by red dots in Materialise Mimics. **(c)** Step 2: Import of mandibular plane, circle and tooth apices into the software 3matic to measure the distances between the tooth apices and the circle centre at T0 and T1

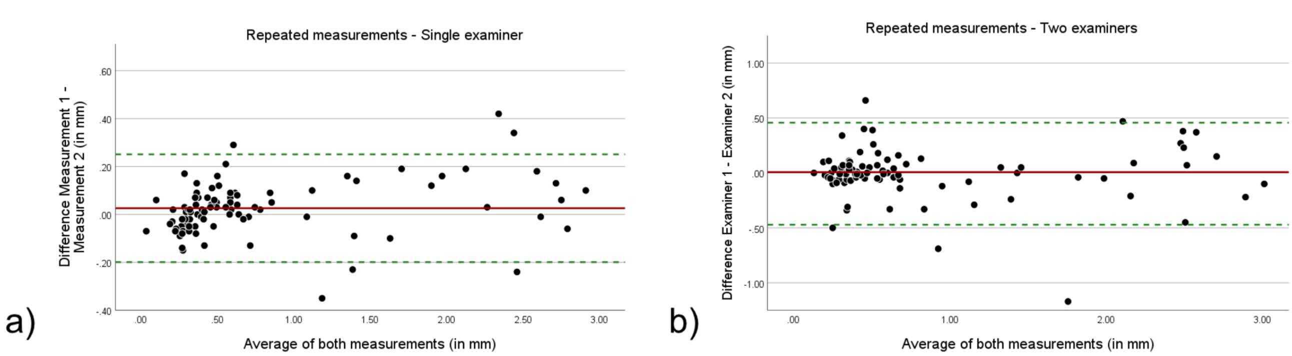

Fig. 5 Bland-Altman plots of repeated measurements, (**a**) of repeated measurements by the same examiner, and (**b**) of two different examiners

Table 1 Relative and absolute reliability assessment of repeated measurements

	ICC (95% CI)	Bias			Repeat-abilityco-efficient (mm)
		Mean diff (SD)	95% CI	*p*-value	
Inter-rater agreement	0.975 (0.962–0.984)	-0.007 (0.237)	-0.057–0.043	0.781	±0.46
Intra-rater agreement	0.988 (0.982–0.992)	0.026 (0.115)	0.002–0.050	0.035*	±0.23

*p-values < 0.05 were considered statistically significant

the apex moved lingually by a mean of 1.08 ± 0.79 mm. In contrast, initially proclined teeth exhibited a comparatively minor mean increase in inclination of 2.10 ± 3.83 degrees ($p = 0.024$), accompanied by a relatively limited mean apex movement of 0.15 ± 1.07 mm ($p = 0.049$). However, the standard deviation indicates a considerable degree of variability.

The change in free gingival thickness during tooth movement differed significantly between initially proclined and retroinclined incisors. Specifically, initially retroinclined teeth showed a small decrease in free gingival thickness (FGT) of 0.10 ± 0.79 mm during orthodontic treatment, whereas proclined teeth showed a small increase of 0.12 ± 0.18 mm ($p < 0.001$). Similarly, the direction of tooth tipping did significantly affect FGT (Table 5). Here, tooth reclination resulted in an increase in gingiva thickness ($p = < 0.001$), with a mean difference of 0.27 mm between the groups. Additionally, tooth proclination was observed to result in a significantly greater reduction in bone height, with a mean difference of 0.50 ± 0.16 mm ($p = 0.048$).

Discussion

The study evaluated soft and hard tissue dimensions around lower anterior teeth before (T0) and after five months of orthodontic treatment (T1) in patients with a mandibular arch length discrepancy of > 3 mm. The results indicate a significant proclination of the lower incisors during the process of orthodontic levelling and

Table 2 Tooth position and tissue dimensions at T0 and T1

		T0 Mean(± SD), median[IQR]	T1 Mean(± SD), median[IQR]	Difference (T0-T1)	
				mean(± SD)	*p*-value°
Inclination (degree)	Incisors ($n = 40$)	90.80(± 9.68)	94.63(± 8.82)	-3.83(± 4.74)	< 0.001*
	Canines ($n = 20$)	93.30(± 6.47)	94.42(± 5.72)	-1.13(± 4.41)	1.000
	All ($n = 60$)	91.63 (± 8.76)	94.56(± 7.88)	-2.93(± 4.77)	< 0.001*
Apex (mm)	Incisors ($n = 40$)	24.58[3.39]	23.94[2.85]	0.61(± 0.93)	< 0.001*
	Canines ($n = 20$)	22.91[3.58]	22.38(± 3.20)	0.14(± 1.17)	1.000
	All ($n = 60$)	24.46[3.92]	23.03[2.87]	0.45(± 1.03)	0.006*
FGT (mm)	Incisors ($n = 40$)	0.72(± 0.25)	0.75(± 0.19)	0.03(± 0.21)	0.338
	Canines ($n = 20$)	0.70[0.28]	0.74[0.17]	-0.04(± 0.16)	1.000
	All ($n = 60$)	0.71(± 0.22)	0.74(± 0.17)	0.03(± 0.19)	0.334
SGT (mm)	Incisors ($n = 40$)	0.80[0.29]	0.75[0.27]	0.07(± 0.19)	0.140
	Canines ($n = 16$)	0.98[0.34]	0.81[0.21]	0.09(± 0.20)	0.816
	All ($n = 56$)	0.85(± 0.75)	0.80(± 0.77)	-0.07(± 0.19)	0.020*
ABT2 (mm)	Incisors ($n = 40$)	0.33[0.21]	0.34[0.27]	-0.02(± 0.15)	0.724
	Canines ($n = 20$)	0.41[0.32]	0.40[0.36]	-0.01(± 0.20)	1.000
	All ($n = 60$)	0.36(± 0.60)	0.36(± 0.57)	0.02(± 0.17)	0.405
ABT4 (mm)	Incisors ($n = 40$)	0.30[0.28]	0.36[0.28]	-0.09(± 0.27)	0.144
	Canines ($n = 20$)	0.47[0.41]	0.49[0.38]	-0.00(± 0.19)	0.954
	All ($n = 60$)	0.34(± 0.52)	0.41(± 0.53)	0.06(± 0.25)	0.112
ABT8 (mm)	Incisors ($n = 39$)	1.47(± 0.75)	2.01(± 0.99)	0.52(± 0.64)	< 0.001*
	Canines ($n = 19$)	1.72(± 0.67)	1.93(± 0.71)	-0.21(± 0.44)	0.441
	All ($n = 58$)	1.55(± 0.73)	1.95(± 0.91)	0.42(± 0.59)	< 0.001*
ABH (mm)	Incisors ($n = 40$)	26.54(± 1.77)	26.18(± 1.69)	-0.37(± 0.55)	< 0.001*
	Canines ($n = 20$)	23.30[3.45]	22.93[3.16]	0.14(± 0.87)	1.000
	All ($n = 60$)	25.40(± 2.50)	25.11(± 2.30)	-0.29(± 0.68)	0.006*
GH (mm)	Incisors ($n = 40$)	30.10(± 1.90)	30.37(± 1.68)	0.27(± 0.84)	0.147
	Canines ($n = 20$)	27.12[3.01]	27.41[2.74]	-0.38(± 1.03)	0.791
	All ($n = 60$)	29.32(± 2.20)	29.63(± 2.01)	0.31(± 0.90)	0.030*

*p-values < 0.05 are considered statistically significant

°Bonferroni-Holm correction was used for multiple testing

Abbreviations: FGT, free gingiva thickness; SGT, supracrestal gingiva thickness; ABT2, alveolar bone thickness 2 mm below the alveolar crest; ABT4, alveolar bone thickness 4 mm below the alveolar crest; ABT8, alveolar bone thickness 8 mm below the alveolar crest; ABH, alveolar bone height; GH, gingiva height

Table 3 Correlation between change in tooth inclination and change in tissue dimensions after 5 months of orthodontic treatment

Region	Tooth type (*N*)	Correlation coefficient (*R*)	*p*-value
ΔFGT	Incisor (40)	-0.681	< 0.001*
	Canine (20)	0.245	1
	All (60)	-0.422	< 0.001*
ΔSGT	Incisor (40)	-0.327	0.80
	Canine (16)	0.179	0.507
	All (56)	-0.161	1
ΔABT2	Incisor (40)	-0.299	0.061
	Canine (20)	-0.261	1
	All (60)	-0.261	0.572
ΔABT4	Incisor (40)	0.162	1
	Canine (20)	0.219	1
	All (60)	0.212	1
ΔABT8	Incisor (39)	0.251	1
	Canine (19)	0.700	< 0.001*
	All (58)	0.404	0.032*
ΔABH	Incisor (40)	-0.574	< 0.001*
	Canine (20)	-0.495	0.39
	All (60)	-0.541	< 0.001*
ΔGH	Incisor (40)	-0.218	1
	Canine (20)	-0.350	1
	All (60)	-0.269	0.532

*p-values < 0.05 are considered statistically significant

°Bonferroni-Holm correction was used for multiple testing

Abbreviations: FGT, free gingiva thickness; SGT, supracrestal gingiva thickness; ABT2, alveolar bone thickness 2 mm below the alveolar crest; ABT4, alveolar bone thickness 4 mm below the alveolar crest; ABT8, alveolar bone thickness 8 mm below the alveolar crest; ABH, alveolar bone height; GH, gingiva height

Table 4 Correlation between movement of the Tooth's apex in buccal direction and change in tissue dimensions after 5 months of orthodontic treatment

Region	Tooth type (*N*)	Correlation coefficient (*R*)	*p*-value
ΔFGT	Incisor (40)	0.356	0.456
	Canine (20)	-0.335	1
	All (60)	0.130	1
ΔSGT	Incisor (40)	0.120	1
	Canine (16)	-0.503	0.846
	All (56)	-0.100	1
ΔABT2	Incisor (40)	0.111	1
	Canine (20)	-0.214	1
	All (60)	-0.040	1
ΔABT4	Incisor (40)	-0.139	1
	Canine (20)	-0.444	0.850
	All (60)	-0.252	0.832
ΔABT8	Incisor (39)	-0.274	1
	Canine (19)	-0.608	0.12
	All (58)	-0.392	0.042*
ΔABH	Incisor (40)	-0.117	1
	Canine (20)	0.076	1
	All (60)	0.013	1
ΔGH	Incisor (40)	0.107	1
	Canine (20)	-0.008	0.974
	All (60)	0.069	1

*p-values < 0.05 are considered statistically significant

°Bonferroni-Holm correction was used for multiple testing

Abbreviations: FGT, free gingiva thickness; SGT, supracrestal gingiva thickness; ABT2, alveolar bone thickness 2 mm below the alveolar crest; ABT4, alveolar bone thickness 4 mm below the alveolar crest; ABT8, alveolar bone thickness 8 mm below the alveolar crest; ABH, alveolar bone height; GH, gingiva height

aligning, with an average angle change of 3.83°. This was accompanied by a movement of the lingual apex of 0.61 mm and a reduction in buccal alveolar bone height of 0.37 mm. No statistically significant changes in tooth position or tissue parameters could be observed in the canines. As gingival recessions are preceded by a lack of bone around the tooth, the lower crestal bone level might contribute to the development of gingival recessions around lower incisors. This knowledge contributes to the existing body of evidence on the incidence of gingival recessions after orthodontic treatment.

The inclination of the lower anterior teeth relative to the mandibular plane is conventionally measured using lateral cephalograms [21]. This approach, however, is limited to providing an average inclination value for all incisors due to the superposition of multiple teeth. In the current study, following the initial alignment phase, the incisors exhibited a proclination of 3.83 ± 4.74 degrees. This finding aligns with prior research by Hennessy et al. [22], who assessed the average proclination of lower incisors in subjects with mild to moderate mandibular crowding of 2.1 mm with cephalograms, noting a post-orthodontic treatment proclination of 5.4 ± 4.3 degrees using fixed appliances. Conversely, a study focusing on incisors in Class III patients recorded a significant proclination shift in the lower anterior teeth from 78.79 degrees to 90.12 degrees, likely attributed to the preoperative orthodontic decompensation of Class III [21].

In the present study, canines exhibited a mild proclination of 1.13 degrees despite the substantial crowding observed in the lower jaw. A comparable outcome was documented in a study that employed three-dimensional measurements derived from CBCT scans of patients undergoing orthodontic treatment due to lower anterior crowding [23]. The authors reported a buccolingual angulation change of 1.64 degrees in canines, in comparison to 3.17 degrees in incisors.

A significant correlation of $R = 0.404$ between changes in tooth inclination and apical bone thickness (ABT8) was observed in the present study. However, the results of the subgroup analysis indicated that this correlation was only statistically significant for canines ($R = 0.700$, $p < 0.001$). This finding is even more pronounced than the results of a previous study, that investigated the impact of tooth inclination on bone dimensions [24]. The study concluded that there was a significant correlation between apical bone thickness and tooth inclination in canines, with a correlation coefficient of $R = 0.36$. With

Table 5 Change of parameters during orthodontic treatment in relation to initial tooth inclination (T0) and change of tooth inclination (T1-T0) during treatment in incisors

		Retroinclined tooth (T0)	Proclined tooth (T0)	Reclination (T1-T0)	Proclination (T1-T0)
Inclination change (degree)	N	16	24	8	32
	Mean(± SD)	6.44(± 5.36)	2.10(± 3.38)	-2.19(± 1.42)	5.34(± 4.01
	Mean difference (± SE)	4.34(± 1.38)		7.52(± 1.45)	
	p-value	0.024*		< 0.001*	
Apex movement in buccal direction (mm)	N	16	24	8	32
	Mean(± SD)	-1.08(± 0.79)	-0.15(± 1.07)	-0.56 ± 0.59	-0.62(± 1.00)
	Mean difference (± SE)	0.79 ± 0.23		0.06 ± 0.37	
	p-value	0.049*		1.000	
ΔFGT (mm)	N	16	24	8	32
	mean(± SD)	-0.10(± 0.17)	0.12(± 0.18)	0.24(± 0.18)	-0.02(± 0.18)
	Mean difference (± SE)	0.23(± 0.06)		0.27(± 0.07)	
	p-value	< 0.001*		< 0.001*	
ΔSGT (mm)	N	16	24	8	32
	mean(± SD)	-0.12(± 0.21)	-0.04(± 0.17)	-0.04(± 0.19)	-0.08(± 0.19)
	Mean difference (± SE)	0.08(± 0.06)		0.03(± 0.08)	
	p-value	0.955		1.000	
ΔABT2 (mm)	N	16	24	8	32
	mean(± SD)	-0.01(± 0.14)	0.05(± 0.16)	0.10(± 0.18)	0.00(± 0.14)
	Mean difference (± SE)	0.06(± 0.05)		0.09(± 0.06)	
	p-value	0.976		0.798	
ΔABT4 (mm)	N	16	24	8	32
	mean(± SD)	0.09(± 0.23)	0.10(± 0.30)	0.10(± 0.13)	0.09(± 0.30)
	Mean difference (± SE)	0.01(± 0.09)		0.01(± 0.11)	
	P-value	0.918		0.959	
ΔABT8 (mm)	N	15	24	8	31
	mean(± SD)	0.51(± 0.47)	0.53(± 0.73)	0.23(± 0.73)	0.59(± 0.60)
	Mean difference (± SE)	0.02(± 0.21)		0.37(± 0.25)	
	p-value	0.932		0.750	
ΔABH (mm)	N	16	24	8	32
	mean(± SD)	-0.42(± 0.61)	-0.34(± 0.53)	0.03(± 0.37)	-0.47(± 0.55)
	Mean difference (± SE)	0.08(± 0.18)		0.50(± 0.16)	
	p-value	1.00		0.048*	
ΔGH (mm)	N	16	24	8	32
	mean(± SD)	-0.04(± 0.95)	0.48(± 0.70)	-0.01(± 0.68)	0.34(± 0.87)
	Mean difference (± SE)	0.52(± 0.26)		-0.35(± 0.33)	
	p-value	0.336		1.000	

*p-values < 0.05 are considered statistically significant

°Bonferroni-Holm correction was used for multiple testing

Δ indicates the change in tissue dimensions after 5 months of treatment (T1-T0)

Abbreviations: FGT, free gingiva thickness; SGT, supracrestal gingiva thickness; ABT2, alveolar bone thickness 2 mm below the alveolar crest; ABT4, alveolar bone thickness 4 mm below the alveolar crest; ABT8, alveolar bone thickness 8 mm below the alveolar crest; ABH, alveolar bone height; GH, gingiva height

regard to the incisors, the significant correlation was only confirmed for the central incisors ($R = 0.34$), and not for the lateral incisors ($R = 0.12$).

In the present study, the lingual displacement of the apex between the timepoints T0 and T1 was 0.45 ± 1.03 mm. The definition of apex movement was the change in the Euclidean distance from the apex to the centre of a hypothetical circle, of which the curvature mimics the anterior segment of the mandible and which runs parallel to the mandibular plane. Previous methods of assessing apex movement have involved superimposing lateral cephalometric radiographs to measure the shift between the apex positions at T0 and T1 [25]. Using this method, Baik et al. [25] observed that the apex retracted by approximately 0.26 mm, while the lower incisors exhibited a tipping movement after premolar extraction. Conversely, another investigation measured apex displacement in the maxilla as the change in distance between the apex of the maxillary incisors and the palatal cortical bone, utilizing sagittal CBCT reconstructions [26]. In this context, following premolar extraction, an apex displacement of 1.0 mm for the central incisors and of 1.9 for lateral incisors was measured.

The current study observed that the lingual displacement of the tooth apex was negatively correlated with the change of the tooth's inclination angle. However, the apex displacement itself did not significantly impact the peri-tooth tissues, potentially due to the minimal extent of apex movement, as suggested by the narrow 95% CI, ranging from −0.72 to -0.18 mm. In contrast, the variation in tooth inclination was more pronounced, with an average proclination of 2.93 degrees and a 95% CI extending from 1.70 to 4.16 degrees. As the apex position remained relatively stable, while the tooth axis experienced a buccal tipping during treatment, it is plausible to assume a controlled tipping of the tooth, resulting in a buccal shift of the crown. Notably, the inverse correlation between apex displacement and the tooth axis' tipping motion was more pronounced in canines ($R = 0.600$), indicating a lesser degree of controlled tipping in canines compared to the incisors. Furthermore, subgroup analysis indicated that teeth presenting retrocinlination underwent more pronounced buccal tipping during orthodontic therapy compared to those with an initial inclination of 90 degrees or more.

The ABH decreased by 0.29 ± 0.68 mm between T0 and T1. A systematic review described a labial vertical bone loss of 0.97 mm around the mandibular incisors [27]. The difference in the severity of the ABH change may be due to the different observation periods, as the patients were re-evaluated at the end of orthodontic treatment and not after 5 months as in the current study. The systematic review identified only three studies that examined changes in labial bone height during orthodontic treatment around mandibular incisors. Four studies reported changes in labial alveolar bone thickness (ABT) during orthodontic treatment, but according to the review, changes in bone thickness remain controversial. In the present study, ABT at the measuring points 2 mm and 4 mm below the alveolar crest (ABT_{2mm}, ABT_{4mm}) remained stable, whereas ABT_{8mm} increased by 0.42 ± 0.59 mm. This increase in ABT_{8mm} is consistent with the findings of Sun et al. [21], who observed a 1.71 ± 0.43 mm increase in labial alveolar bone thickness at the apical level of the mandibular incisors after preoperative orthodontic treatment in patients with class III malocclusion. As noted above, the mandibular incisors in Sun's study were highly proclined in the course of treatment, which may explain the increased bone gain around the tooth apex.

To quantitatively evaluate changes in soft and hard tissue during tooth movement, studies use tooth-related landmarks [28, 29] or register the patient's head or jaw into a 3D coordinate system [10, 29]. To measure tooth movements during orthodontic treatment, relying on the individual tooth's axis as a landmark is unreliable due to its constant changes. Therefore, it is mandatory to establish a stable jaw- or head-related reference plane or coordinate system [30]. In this study, the mandibular plane was used after superimposing MRI images from both time points. This allowed the registration of tooth apex position and tooth angulation before and after the start of orthodontic treatment.

It is important to note that clinically significant tooth movements do not always follow a coordinate system consisting of changes around an x- and y-axis. Rather, they occur along the dental arch, which has a curvature. Buccally directed movement of teeth is clinically relevant because it brings teeth closer to the border of the alveolar bone ridge, thereby increasing the risk of gingival recessions and bone dehiscence. Guo et al. measured the buccolingual inclination and movement of anterior teeth by calculating the 3D-coordinate differences between T0 and T1 [29]. The movement of the canines differed from that of the incisors due to convex nature of the labial aspect of the anterior mandible. During orthodontic retraction, the incisors move strictly posteriorly along the sagittal axis, while the canines, which are positioned along the anterior curvature of the dental arch, shift along both the sagittal and transversal axes. To enhance the clinical interpretability of the results, the current study describes the bucco-lingual tooth movements of the anterior teeth along the dental arch, represented by a circular sketch following the anterior curvature of the mandible, rather than using a 3D-coordinate system.

This pilot study has four main limitations that could be addressed in future research. Firstly, the sample size was limited to only ten patients, which is sufficient for a pilot study, but larger studies will be required to increase the representativeness of the results. The majority of measurements taken around the canines did not reach a statistically significant level. It is possible that the observed changes in tissue dimensions were relatively subtle, which may have contributed to the lack of significant findings. Alternatively, the limited number of measurements, with only 20 canines analysed, may have been a factor.

Secondly, the analysis of tooth movement focused on tooth inclination and bucco-lingual movements, but did not consider rotational and apico-coronal tooth movements. Even though straight archwires were used without the intention of inducing significant vertical changes, it is important to note that intrusive forces on the anterior segment of the mandible might still have been present. These forces, although not specifically targeted by the archwire design, may occur during the initial orthodontic levelling and aligning phase. This aspect of potential intrusive forces on the anterior mandibular segment was not accounted for in the present investigation and should be carefully considered in future studies to fully understand the dynamics of tooth movement during treatment.

Thirdly, although the study methodology was prospective and standardised, there were issues such as the exclusion of three images due to motion artefacts, highlighting the sensitivity of MRI to motion. This is a particular challenge in younger patients where it is difficult to keep still for image quality. Finally, the study timeframe was limited to a pre-treatment examination and a five-month follow-up during the initial phase of orthodontic treatment, during which significant changes in periodontal parameters and tooth positions were observed. Future research could benefit from longer follow-up periods to capture changes at different stages of treatment.

Further studies are encouraged to explore different aspects to advance orthodontic therapy. Investigating new parameters, such as considering changes in tooth rotation or intrusion during therapy, could provide a more nuanced understanding of the relationship between tooth movement and changes in periodontal dimensions. Comparing different treatment modalities, such as tooth extraction versus non-extraction therapy, or traditional straightwire techniques versus aligner therapy, could provide insights into the effects of orthodontic approaches on tooth movement and periodontal parameters.

Conclusion

The study presents an MRI-based method for assessing the orthodontic movement of mandibular anterior teeth and associated tissue changes, suggesting MRI as a radiation-free alternative to CBCT for follow-up investigations. The findings suggest that alterations in the inclination of the anterior teeth have a significant impact on the dimensions of the surrounding tissue. However, the relatively small sample size and the presence of motion artefacts in some datasets may have an impact on the reliability and generalizability of the findings.

Abbreviations

ABT	Alveolar Bone Thickness
ABH	Alveolar Bone Height
CBCT	Cone-beam Computed Tomography
FGT	Free Gingiva Thickness
GH	Gingiva Height
IOTN	Index of Orthodontic Treatment Need
IQR	Inter-quartile range
MRI	Magnetic Resonance Imaging
NiTi	Nickel-titanium
R	Correlation Coefficient
SD	Standard Deviation
SGT	Supracrestal Gingiva Thickness
TE	Echo Time
TR	Repetition Time
SAR	Specific Absorption Rate

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Data availability
The datasets generated and analysed during the current study are not publicly available due highly sensitive nature of radiological datasets, but tables with measurements are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the Medical University of Vienna (EK Nr: 1654/2021). Informed consent to participate was obtained from all participants prior to their inclusion in the study.

Consent for publication
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Competing interests
The authors declare no competing interests.

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