The incidence and severity of root resorption following orthodontic treatment using clear aligners

Christopher James Costello,* Brett Kerr,† Tony Weir‡ and Elissa Freer‡
Private Practice, Sydney* and Discipline of Orthodontics, School of Dentistry, University of Queensland, Brisbane,† Australia

Introduction
Orthodontically-induced inflammatory root resorption (OIIRR) is a term used to describe the pathologic loss of tooth structure as a consequence of orthodontic tooth movement.1 As a common and adverse effect of treatment, there is the potential for severe damage and a compromised orthodontic result. In addition, a reduced root length following treatment can subject affected teeth to a greater chance of tooth loss secondary to trauma or periodontal disease. Although Bates was the first to discuss root resorption in 1856, Ottolengui in 1914 related root resorption directly to orthodontics by referring to resorbed roots in extracted permanent teeth previously described by Schwarzkopf in 1887.2 Ketcham reported iatrogenic root resorption as a common consequence of orthodontics in 1927 by radiographically revealing differences in root shape before and after orthodontic treatment.3

Since the relationship between orthodontic tooth movement and resorption was established in the early part of the 20th century, a plethora of radiographic and histologic methods has subsequently become available to investigate, assess, and quantify OIIRR. Contemporary cone beam computed tomography (CBCT) is recognised as the most accurate method of radiographic assessment of OIIRR.4,5

Extensive studies have elucidated a multifactorial aetiology, and identified risk factors that predispose patients to the development of OIIRR. For example, heavy force application has long been associated with greater levels of OIIRR,6 and the use of lighter force levels has been recommended as a method of minimising root damage. In addition, force

Methods: Linear tooth lengths of maxillary and mandibular teeth from the second molar to second molar were measured from pre- and post-treatment cone beam computed tomography examinations of 25 patients who were treated by a clear aligner system. Results: Mean reductions in tooth length varied according to tooth type, with maxillary central and lateral incisors experiencing the most resorption, of 0.5 ± 0.41 mm and 0.4 ± 0.56 mm respectively. All tooth types had most resorption fall within the <0.25 mm range, with 7% of central and lateral incisors accounting for resorption >1.5 mm. Although the level of resorption identified in this study was less than that reported for fixed appliances, overall, the trends were similar. Conclusions: Orthodontic treatment carried out with clear aligners resulted in root resorption that was largely clinically insignificant. There was a general trend towards more resorption affecting anterior teeth in both the maxilla and mandible. Original tooth length was found to be a predictor of the amount of resorption. (Aust Orthod J 2020; 36: 130-137)

Received for publication: February 2020
Accepted: June 2020

Christopher James Costello: drccostello@gmail.com; Brett Kerr: uqbkerr@uq.edu.au; Tony Weir: tony@tonyweir.com.au; Elissa Freer: e.freer@uq.edu.au

Introduction
Orthodontically-induced inflammatory root resorption (OIIRR) is a term used to describe the pathologic loss of tooth structure as a consequence of orthodontic tooth movement.1 As a common and adverse effect of treatment, there is the potential for severe damage and a compromised orthodontic result. In addition, a reduced root length following treatment can subject affected teeth to a greater chance of tooth loss secondary to trauma or periodontal disease. Although Bates was the first to discuss root resorption in 1856, Ottolengui in 1914 related root resorption directly to orthodontics by referring to resorbed roots in extracted permanent teeth previously described by Schwarzkopf in 1887.2 Ketcham reported iatrogenic root resorption as a common consequence of orthodontics in 1927 by radiographically revealing differences in root shape before and after orthodontic treatment.3

Since the relationship between orthodontic tooth movement and resorption was established in the early part of the 20th century, a plethora of radiographic and histologic methods has subsequently become available to investigate, assess, and quantify OIIRR. Contemporary cone beam computed tomography (CBCT) is recognised as the most accurate method of radiographic assessment of OIIRR.4,5

Extensive studies have elucidated a multifactorial aetiology, and identified risk factors that predispose patients to the development of OIIRR. For example, heavy force application has long been associated with greater levels of OIIRR,6 and the use of lighter force levels has been recommended as a method of minimising root damage. In addition, force
 ROOT RESORPTION AFTER CLEAR ALIGNER TREATMENT

interruption by pausing orthodontic treatment has also been reported to be beneficial.\textsuperscript{6–8} Recent systematic reviews and meta-analyses on OIIRR related to fixed appliances and assessed by CBCT concluded that all teeth examined showed some OIIRR, leading to an average root length loss of between 0.80 mm and 0.86 mm. This was clinically considered to be irrelevant.\textsuperscript{9,10}

As techniques for investigating root resorption have evolved, so too have the methods for treating malocclusions. In 1944, the Tooth Positioner from TP Orthodontics, and in 1946 the Kesling appliance, paved the way for the development of contemporary sequential aligner systems for tooth movement, the most ubiquitous, complex and comprehensive of which is the Invisalign\textsuperscript{®} system from Align Technology.\textsuperscript{11} This system allows a computerised 3D CAD-CAM clinician designed treatment plan\textsuperscript{6,8} to be constructed, and makes a greater magnitude of tooth movement feasible.\textsuperscript{12} In 2013, Align Technology\textsuperscript{®} introduced SmartTrack\textsuperscript{®} as a successor to the EX-30\textsuperscript{®} aligner material, claiming that, compared to conventional materials, it conformed to tooth morphology more precisely, and delivered a gentle, more constant force considered ideal for tooth movements.\textsuperscript{13} This may have contributed to the belief by some practitioners that the use of clear aligners to carry out orthodontic treatment is associated with a reduction in root resorption.

The present study aimed to investigate the incidence and severity of apical OIIRR following treatment using the Invisalign appliance, using linear measurements from pre- and post-treatment CBCTs. According to current knowledge, it will be amongst the first studies to evaluate root length loss associated with orthodontic treatment using a clear aligner system.

Materials and methods
This retrospective radiometric study used linear measurements from CBCT scans to assess 994 roots from 25 patients who underwent non-extraction orthodontic treatment using the Invisalign\textsuperscript{®} clear aligner system. An appropriately powered sample size (power = 0.95) was calculated with an alpha value of 0.05, and determined to be 23 participants. Treatment delivery was provided by one orthodontist in a private practice in Sydney, Australia. The patient study sample is described in Table I. There were three male and 22 female patients, presenting with a mean patient age at the commencement of treatment of 31 years 6 months. The average treatment duration was 73.6 weeks. The Angle classification and degree of

| Characteristics          | < 12 months | 12 to 24 months | > 24 months |
|--------------------------|-------------|-----------------|-------------|
| N                        | N (%)       | N (%)           | N (%)       |
| N                        | 7 (28)      | 10 (40)         | 8 (32)      |
| Mean Age (SD)            | 34.9 (14.9) | 23.6 (11.9)     | 35.8 (10.2) |
| Sex                      |             |                 |             |
| Female                   | 6 (27)      | 11 (50)         | 5 (23)      |
| Male                     | 2 (67)      | 1 (33)          | -           |
| Malocclusion status      |             |                 |             |
| Class I                  | 4 (36)      | 5 (45)          | 2 (18)      |
| Class II                 | 2 (17)      | 5 (42)          | 5 (42)      |
| Class III                | 1 (50)      | -               | 1 (50)      |
| Crowding Upper           |             |                 |             |
| None                     | 1 (100)     | -               | -           |
| Mild                     | 5 (38)      | 6 (43)          | 3 (21)      |
| Moderate                 | 2 (20)      | 6 (60)          | 2 (20)      |
| Crowding Lower           |             |                 |             |
| None                     | 1 (100)     | -               | -           |
| Mild                     | 3 (33)      | 4 (44)          | 2 (22)      |
| Moderate                 | 4 (27)      | 7 (47)          | 4 (27)      |
crowding within each arch was assessed using Little’s Irregularity Index.

The criteria for selection of the study group were identified as those requiring complete orthodontic treatment with removable aligners; having complete root formation with the absence of pathology; no previous history of dental trauma or orthodontics; no anteroposterior correction of the malocclusion required; resolution of crowding by expansion; no teeth that had undergone root canal treatment; available treatment records and pre- and post-treatment CBCTs of diagnostic quality.

Ethics approval was obtained from The University of Queensland Human Research Ethics Committee. Informed consent from the patients was granted prior to the acquisition of CBCT images and the commencement of orthodontic treatment.

A Galileos Comfort Plus (Sirona, Germany) 3D imaging system was used to obtain the CBCT images before and after treatment. The scans were acquired using 98 kVp, 6 mA, voxel size 0.25 mm, and a scan time of 14 seconds. The captured images were reconstructed in Digital Imaging and Communications in Medicine (DICOM) files, de-identified through the Galaxis export ‘anonymize’ functionality, and saved to an encrypted external hard drive (Toshiba Corporation, Japan).

The DICOM files were imported into Mimics (Materialise, Belgium) for the identification of reference points and measurement analysis on a Windows 10 workstation (Microsoft Corp., WA, USA), with Intel Core i7-6600U 71 GHz processor (Intel Corporation, CA, USA), NVIDIA GeForce GTX 965M (2GB GDDR5) graphics card (NVIDIA Corporation, CA, USA), and Dell Monitor, at a resolution of 1920 × 1080 pixels (Dell, TX, USA).

The analysis of OIIRR was undertaken by the method described by Castro et al. The landmarks used for measurement purposes are illustrated in Figure 1.

The greatest length between the cuspal edges and root apices was calculated using axial multiplanar reconstruction (Figure 2), whereby the axial movement of the cursor on sagittal or coronal reconstruction aided in defining the reference points. These points were defined by the intersection of the sagittal or coronal cursor with the axial cursor. The lengths between the reference points were measured in the sagittal or coronal multiplanar reconstruction and provided measurements to one-tenth of a millimetre. All measurements between timepoints were blinded and carried out by one operator (C.C.).

OIIRR was measured by comparing pre- and post-treatment tooth lengths, and data were recorded using Microsoft Office Excel™ (Microsoft Corp., WA, USA).

![Figure 1. Reference Points Used for Linear Measurement. (Adapted from Castro et al.14)](image)
Descriptive analysis was used to assess the frequency of root resorption, which was categorised as <0.25, 0.25-0.75, 0.75-1.5, and >1.5 mm for each tooth root. The severity of root resorption was assessed using dependent and independent samples t-test. Multiple linear regression was applied to assess associations between treatment duration and tooth location relative to the root resorption.

Measurements were repeated on 20 randomly selected teeth from the data set six weeks following the initial measurement. The intra-rater reliability was assessed using a two-way random-effect model intra-class correlation coefficient (ICC) with absolute agreement to assess the level of reliability between the measurements taken two weeks apart. The ICC value was high (ICC = 0.99, 95% CI 0.98, 1.00), indicating a high level of reliability and suggesting that the measurements were obtained similarly at the two time points. Data were subjected to statistical analysis performed in Stata (StataCorp, TX, USA; Version 14.1).

Results

The mean reduction in tooth length is described in Table II. All tooth types demonstrated a statistically significant reduction in length, with anterior teeth in both arches displaying more resorption than posterior teeth. The maxillary central incisors underwent the greatest mean reduction in length of 0.5 ± 0.41 mm (p < 0.0001). The maxillary lateral incisors and canines, and lower anterior teeth experienced similar levels of resorption, revealed by a 0.4 ± 0.56 mm reduction in length. The mesial root of the lower second molar demonstrated the least mean amount of resorption of 0.1 ± 0.19 mm (p = 0.019).

Table III describes resorption when analysed in association with Angle classification and crowding status. There were no statistically significant differences within the sample, apart from the lower canines experiencing 0.59 mm OIIRR in mildly crowded cases and 0.22 mm OIIRR in moderately crowded cases (p = 0.015).

All tooth types had their greatest level of resorption fall within the <0.25 mm range, as described in Table IV and Figure 3. The central and lateral incisors demonstrated the highest frequency of resorption of >1.5 mm, accounting for 7% of the sample. In contrast, the majority of the canines, premolars and molars experienced <1.5 mm resorption, with only 1% of the sample exhibiting resorption >1.5 mm.

Neither treatment duration nor location of the tooth within either the maxilla or mandible were found to be predictors of resorption (Table V). However, the original tooth length was found to correlate with the level of root resorption (p < 0.001).

Discussion

The aims of the present study were to assess the incidence and severity of OIIRR following clear aligner treatment. Resorption was found to be ubiquitous within the sample, as all patients experienced multiple instances across tooth types and between the arches. It was found that maxillary central incisors exhibited the greatest severity of resorption, with a mean reduction in tooth length of 0.5 ± 0.41 mm. Similarly, maxillary lateral incisors also demonstrated a relatively high mean level of resorption of 0.4 ± 0.56 mm. Interestingly, this is in high agreement with the findings of Aman et al. who, in their Invisalign-treated sample,
Table II. Tooth length averaged across side for pre- and post-treatment by root type.

| Arch     | Tooth              | Root | N   | Mean (SD) | Mean (SD) | Mean (SD) | P-value | 95% CI |
|----------|--------------------|------|-----|-----------|-----------|-----------|---------|--------|
| Maxillary | Central incisor   | SR   | 25  | 23.7 (2.16) | 23.2 (2.18) | -0.5 (0.41) | < .0001 | 0.3, 0.7 |
|          | Lateral incisor   | SR   | 25  | 22.9 (2.09) | 22.5 (2.12) | -0.4 (0.56) | .001    | 0.2, 0.6 |
|          | Canine            | SR   | 25  | 25.8 (2.40) | 25.4 (2.61) | -0.4 (0.35) | < .0001 | 0.2, 0.5 |
|          | First premolar    | BR   | 25  | 20.9 (1.51) | 20.6 (1.48) | -0.3 (0.37) | .0002   | 0.2, 0.5 |
|          |                   | PR   | 18  | 19.9 (1.55) | 19.6 (1.63) | -0.3 (0.30) | .0007   | 0.1, 0.4 |
|          | Second premolar   | BR   | 25  | 20.7 (1.85) | 20.5 (1.85) | -0.2 (0.37) | .003    | 0.1, 0.4 |
|          |                   | PR   | 2   | 20.0 (1.70) | 19.8 (1.99) | -0.2 (0.30) | .57     | -2.5, 2.8 |
|          | First molar       | DBR  | 25  | 19.5 (1.53) | 19.3 (1.47) | -0.3 (0.28) | .0002   | 0.1, 0.4 |
|          |                   | MBR  | 25  | 19.3 (1.40) | 19.2 (1.30) | -0.2 (0.29) | .011    | 0.0, 0.3 |
|          |                   | PR   | 25  | 21.4 (1.44) | 21.1 (1.44) | -0.3 (0.30) | < .0001 | 0.2, 0.4 |
|          | Second molar      | DBR  | 17  | 19.4 (1.20) | 19.2 (1.30) | -0.2 (0.25) | .012    | 0.1, 0.3 |
|          |                   | MBR  | 23  | 19.4 (1.33) | 19.1 (1.24) | -0.3 (0.45) | .005    | 0.1, 0.5 |
|          |                   | PR   | 19  | 20.6 (1.57) | 20.4 (1.50) | -0.2 (0.25) | .002    | 0.1, 0.3 |
| Mandibular | Central incisor | SR   | 25  | 21.3 (1.46) | 20.8 (1.47) | -0.4 (0.42) | < .0001 | 0.3, 0.6 |
|          | Lateral incisor   | SR   | 25  | 22.3 (1.80) | 21.9 (1.80) | -0.4 (0.39) | < .0001 | 0.2, 0.6 |
|          | Canine            | SR   | 25  | 25.1 (2.24) | 24.7 (2.19) | -0.4 (0.38) | .0001   | 0.2, 0.5 |
|          | First premolar    | SR   | 25  | 22.1 (1.58) | 21.7 (1.68) | -0.3 (0.29) | < .0001 | 0.2, 0.4 |
|          | Second premolar   | SR   | 24  | 21.8 (1.80) | 21.6 (1.71) | -0.2 (0.25) | .0004   | 0.1, 0.3 |
|          | First molar       | DR   | 25  | 20.1 (1.19) | 19.9 (1.23) | -0.2 (0.22) | .0001   | 0.1, 0.3 |
|          |                   | MR   | 25  | 20.7 (1.08) | 20.5 (1.19) | -0.2 (0.24) | .0001   | 0.1, 0.3 |
|          | Second molar      | DR   | 23  | 19.4 (1.94) | 19.3 (1.20) | -0.2 (0.21) | .001    | 0.1, 0.2 |
|          |                   | MR   | 25  | 19.9 (1.66) | 19.8 (1.69) | -0.1 (0.19) | .019    | 0.0, 0.2 |

Note: p-values less than 0.05 indicate a statistically significant difference in tooth length after orthodontic treatment.

Figure 3. Level of resorption by tooth type.

Level of Resorption Classified by Tooth Type

- **Molar**
- **Pre-molar**
- **Canine**
- **Lateral Incisor**
- **Central Incisor**

* Buccal roots only
** Mesiobuccal or distobuccal only
reported a mean level of 0.47 ± 0.61 and 0.55 ± 0.7 mm OIIRR in central and lateral incisors, respectively. Similarly, Eissa et al.,16 in their prospective pilot study, also reported similar findings of 0.44 ± 0.35 mm OIIRR in maxillary incisors of an Invisalign-treated group.

There was a general trend towards the anterior teeth exhibiting more resorption in both arches, and central and lateral incisors were found to be the most commonly-affected teeth with resorption levels >1.5 mm. Although there was no fixed appliance control group used in the study by Eissa et al.,16 it is prudent to note that a recent systematic literature review by Samandara et al.,17 concerning the evaluation of root resorption by CBCT in orthodontically-treated cases using fixed appliances, identified the same trends. A

Table III. Average measure of change in tooth length after treatment analysed by malocclusion and crowding status.

| Arch       | Tooth                    | Malocclusion status | Crowding | p     | None/Mild | Moderate | p     |
|------------|--------------------------|---------------------|----------|-------|-----------|----------|-------|
| Maxillary  | Central incisor          | SR                  | Class I  | 0.37  | 0.59      | 0.17     | 0.47  | 0.54  | .69    |
|            |                          | (-0.64, -0.09)      | (-0.82, -0.37) | .15  | (-0.67, -0.26) | (-0.88, -0.19) | .92    |
| Lateral incisor | SR                  | (-0.45, -0.003)      | (-0.94, -0.17) | .15  | (-0.75, -0.09) | (-0.78, -0.01) | .48    |
| Canine     | SR                       | (-0.48, -0.08)      | (-0.69, -0.24) | .20  | (-0.54, -0.15) | (-0.70, -0.19) | .96    |
| First premolar | BR                  | (-0.45, -0.06)      | (-0.63, -0.14) | .39  | (-0.51, -0.14) | (-0.63, -0.01) | .96    |
|            |                          | (-0.27)             | (-0.32)     | .73  | (-0.55, -0.14) | (-0.41, 0.05) | .28    |
| Second premolar | BR                  | (-0.44, -0.10)      | (-0.40, -0.09) | .80  | (-0.36, 0.08) | (-0.36, 0.12) | .38    |
| First molar | BR                       | (-0.23)             | (-0.26)     | .78  | (-0.45, 0.08) | (-0.37, 0.08) | .72    |
|            |                          | (-0.45, -0.09)      | (-0.63, -0.01) | .39  | (-0.51, -0.14) | (-0.63, -0.01) | .96    |
| Second molar | BR                  | (-0.27)             | (-0.25)     | .73  | (-0.55, -0.14) | (-0.41, 0.05) | .38    |
| Central incisor | SR                  | (-0.43, -0.12)      | (-0.65, -0.18) | .94  | (-0.63, 0.06) | (-0.72, 0.23) | .46    |
| Lateral incisor | SR                  | (-0.39)             | (-0.41)     | .88  | (-0.57, 0.14) | (-0.68, 0.18) | .65    |
| Canine     | SR                       | (-0.49)             | (-0.27)     | .16  | (-0.80, 0.37) | (-0.42, 0.02) | .015   |
| First premolar | SR                  | (-0.49, -0.14)      | (-0.51, -0.13) | .96  | (-0.51, -0.13) | (-0.49, -0.15) | .99    |
| Second premolar | SR                  | (-0.20)             | (-0.22)     | .87  | (-0.54, 0.02) | (-0.27, -0.02) | .29    |
| First molar | DR                       | (-0.13)             | (-0.27)     | .11  | (-0.20, 0.05) | (-0.41, 0.12) | .12    |
|            |                          | (-0.23, -0.03)      | (-0.42, -0.12) | .15  | (-0.20, 0.05) | (-0.41, 0.12) | .23    |
| Second molar | DR                       | (-0.23)             | (-0.36, -0.10) | .99  | (-0.28, 0.03) | (-0.43, 0.13) | .31    |
|            |                          | (-0.38, -0.08)      | (-0.20, -0.01) | .11  | (-0.40, 0.03) | (-0.23, 0.02) | .63    |

Notes: Values in parentheses are 95% CIs. Abbreviations: SR = Single Root; BR = Buccal Root; PR = Palatal Root; DBR = Distal Buccal Root; MBR = Mesio Buccal Root; DR = Distal Root; MR = Mesial Root
mean overall resorption loss of 0.86 mm was found, with central and lateral incisors exhibiting the greatest mean loss of 1.00 mm and 0.83 mm, respectively.\textsuperscript{17} Although the study by Samandara et al.\textsuperscript{16} identified less OIIRR using aligners, caution must be exercised in comparisons or extrapolations, given the disparity between the samples examined.

There was no association found between Angle classification and resorption, despite associations being identified in previous studies.\textsuperscript{18,19} This is likely related to the inclusion criteria used in the present study, which specified that only cases requiring no anteroposterior change and treated on a non-extraction basis were to be assessed. This was done to ensure that all malocclusion types were represented, yet confounders such as elastic wear were eliminated. Consequently, there was no large tooth movement similar to that required in the management of Class II division I malocclusions aiming to completely normalise the overjet. Significant tooth movement would likely affect the level of resorption.

In contrast to Aman et al.,\textsuperscript{15} the present study found no association between the degree of crowding and OIIRR. The results should be interpreted with caution, as the baseline characteristics of the sample were defined by mild or moderate levels of crowding.

Only one subject had no crowding, and so the sample may have been too small to detect a significant difference.

In contrast to previous studies concerning treatment duration,\textsuperscript{20} no association with root resorption was detected in the current study. This result may be explained by the intermittent forces delivered by clear aligners to achieve the desired corrective tooth movement. Frequently, the goals of treatment are not met in the initial phase of alignment and a ‘refinement’ is required, necessitating a new series of aligners. Consequently, there is a variable latency period that may allow the repair of resorptive lesions and the prevention of further root loss.\textsuperscript{21,22} Additionally, stress relaxation is a property of viscoelastic aligner materials such as SmartTrack\textsuperscript{TM}, which indicates that the force generated by an appliance decreases with time.\textsuperscript{23}

The sample characteristics prohibited an analysis of the effect of gender on root resorption in the present study, as only three males were represented in the cohort. However, current evidence suggests this is equivocal, with most studies finding little association.\textsuperscript{7,24,25}

It has been demonstrated that the error in measuring tooth lengths is reduced when a voxel size of 0.2 mm or less is applied when compared with two-dimensional radiographic techniques.\textsuperscript{26} The present study assessed CBCT volumes obtained with a voxel size of 0.25 mm. The use of this protocol appears justified in view of the increased radiation exposure necessary to further reduce the voxel size for the detection of largely clinically insignificant amounts of root resorption. Nevertheless, there is potentially an underestimation of OIIRR at this resolution. Additionally, the present study utilised linear measurements derived from CBCT scans for the detection of apical root resorption. OIIRR is a

| Table IV. Percentages of teeth categorised by level of resorption. The modal class of root was used for multi-root teeth. |
|---|---|---|---|---|
| Type of tooth | Percentage of tooth type with no resorption (< 0.25 mm) | Percentage of tooth type with low resorption (0.25 - 0.75 mm) | Percentage of tooth type with moderate resorption (0.75 - 1.5 mm) | Percentage of tooth type with high resorption (> 1.5 mm) |
| Central incisor | 48 | 29 | 16 | 7 |
| Lateral incisor | 52 | 26 | 15 | 7 |
| Canine | 46 | 33 | 20 | 1 |
| Pre-molar\textsuperscript{4} | 58 | 26 | 15 | 1 |
| Molar\textsuperscript{5} | 66 | 25 | 8 | 1 |

\textsuperscript{4}Buccal roots only
\textsuperscript{5}Mesial-buccal or mesial only

| Table V. Regression coefficients predicting resorption. |
|---|---|---|
| Independent variables | Coefficient (95% CI) | p |
| Treatment time (years) | 0.055 (0.058, 0.167) | 0.34 |
| Tooth length (mm) | 0.045 (0.024, 0.066) | < 0.001 |
| Mandible | Reference |
| Maxillary | -0.061 (-0.163, 0.042) | 0.25 |
three-dimensional phenomenon affecting all surfaces of the tooth, and therefore it would be appropriate for further prospective studies to volumetrically assess the level of resorption, and for correlation against projected and planned tooth movements. In addition, OIIRR associated with a range of malocclusions treated by extraction or non-extraction is worthy of future investigation. Fixed appliance control groups would enhance the validity of future studies.

Conclusions

- All patients experienced root resorption in multiple tooth types and locations.
- Invisalign treatment resulted in largely clinically insignificant levels of root resorption, with the maxillary central and lateral incisors experiencing the greatest mean reduction of 0.5 ± 0.41 mm and 0.4 ± 0.56 mm, respectively.
- These findings, although less than those for fixed appliances, show similar trends, with no direct comparison possible given sample differences.
- There was a general trend towards anterior teeth exhibiting more resorption in both the maxilla and mandible, and central and lateral incisors were found to be the most commonly affected teeth with resorption levels >1.5 mm, accounting for 7% of the sample.
- Original tooth length was found to be a predictor of the amount of resorption.

Conflict of interest
The authors declare that there is no professional or financial conflict of interest.

References

1. Brezniak N, Wasserstein A. Orthodontically induced inflammatory root resorption. Part I: The basic science aspects. Angle Orthod 2002;72:175-9.
2. McCoy JR. Review of orthodontic literature for 1914. International Journal of Orthodontia 1915;1:325-9.
3. Brezniak N, Wasserstein A. Root resorption after orthodontic treatment: Part 1. Literature review. Am J Orthod Dentofacial Orthop 1993;103:62-6.
4. Wang Y, He S, Yu L, Li J, Chen S. Accuracy of volumetric measurement of teeth in vivo based on cone beam computer tomography. J Craniomaxillofac Surg 2013;41:491-6.
5. Wang Y, He S, Yu L, Li J, Chen S. Accuracy of volumetric measurement of teeth in vivo based on cone beam computer tomography. J Craniomaxillofac Surg 2013;41:491-6.
6. Weltman B, Vig KW, Fields HW, Shanker S, Kazear EE. Root resorption associated with orthodontic tooth movement: A systematic review. Am J Orthod Dentofacial Orthop 2010;137:462-76.
7. Sameshima GT, Sinclair PM. Predicting and preventing root resorption: Part II. Treatment factors. Am J Orthod Dentofacial Orthop 2001;119:511-5.
8. Killiyan DM. Root resorption caused by orthodontic treatment: An evidence-based review of literature. Seminars orthod 1999;5:128-33.
9. Deng Y, Sun Y, Xu T. Evaluation of root resorption after comprehensive orthodontic treatment using cone beam computed tomography (CBCT): a systematic review and meta-analysis. Eur J Orthod 2019;41:67-79.
10. Samandara A, Papageorgiou SN, Ioannidou-Marathioudou I, Kavvadia-Tsatala S, Papadopoulos MA. Evaluation of orthodontically induced external root resorption following orthodontic treatment using cone beam computed tomography (CBCT): a systematic review and meta-analysis. Eur J Orthod 2019;41:67-79.
11. Weir T. Clear aligners in orthodontic treatment. Aust Dent J 2017;62 Suppl 1:58-62.
12. Vlaskalic V, Boyd RL. Clinical evolution of the Invisalign appliance. J Calif Dent Assoc 2002;30:769-76.
13. SmartTrack. 2013. Viewed 21 May 2020, <https://bitemagazine.com.au/smarttrack/>.
14. Castro IO, Alencar AH, Valladares-Neto J, Estrela C. Apical root resorption due to orthodontic treatment detected by cone beam computed tomography. Angle Orthod 2013;83:196-203.
15. Amann C, Azevedo B, Bednar N, Chandiramani S, German D, Nicholson E et al. Apical root resorption during orthodontic treatment with clear aligners: A retrospective study using cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2018;153:842-51.
16. Eissa O, Carlyle T, El-Bialy T. Evaluation of root length following treatment with clear aligners and two different fixed orthodontic appliances. A pilot study. J Orthod Sci 2018;7:11.
17. Samandara A, Papageorgiou SN, Ioannidou-Marathioudou I, Kavvadia-Tsatala S, Papadopoulos MA. Evaluation of orthodontically induced external root resorption following orthodontic treatment using cone beam computed tomography (CBCT): a systematic review and meta-analysis. Eur J Orthod 2019;41:67-79.
18. Sameshima GT, Sinclair PM. Predicting and preventing root resorption: Part I. Diagnostic factors. Am J Orthod Dentofacial Orthop 2001;119:505-10.
19. Taner T, Ci er S, Sençift Y. Evaluation of apical root resorption following extraction therapy in subjects with Class I and Class II malocclusions. Eur J Orthod 1999;21:491-6.
20. Brezniak N, Wasserstein A. Root resorption after orthodontic treatment: Part 2. Literature review. Am J Orthod Dentofacial Orthop 1993;103:138-46.
21. Dougherty HL. The effect of mechanical forces upon the mandibular buccal segments during orthodontic treatment. Am J Orthod 1968;54:29-49.
22. Reitan K. Effects of force magnitude and direction of tooth movement on different alveolar bone types. Angle Orthod 1964;34:244-55.
23. Kohda N, Iijima M, Muguruma T, Brantley WA, Ahluwalia KS, Mizoguchi I. Effects of mechanical properties of thermoplastic materials on the initial force of thermoplastic appliances. Angle Orthod 2013;83:476-83.
24. Krishnan V. Critical issues concerning root resorption: a contemporary review. World J Orthod 2005;6:30-40.
25. Beck BW, Harris EF. Apical root resorption in orthodontically treated subjects: analysis of edgewise and light wire mechanics. Am J Orthod Dentofacial Orthop 1994;105:350-61.
26. Lund H, Gröndahl K, Gröndahl H-G. Cone beam computed tomography for assessment of root length and marginal bone level during orthodontic treatment. Angle Orthod 2010;80:466-73.