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Evaluation of External Apical Root Resorption and the Relevance of Intermediate Radiography in Non-Extraction Treatment With Fixed Appliances for Adolescents With Crowding: A Multicenter Randomised Controlled Trial Using CBCT

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ABSTRACT

Objectives: The objectives are to assess the severity and frequency of clinically relevant external apical root resorption (EARR) ≥ 2 mm during orthodontic treatment with Damon passive self-ligating and Victory conventional standardised fixed appliance systems and to evaluate the relevance of intermediate radiographic examinations for early detection and prevention of severe EARR.

Materials and Methods: Adolescents aged 12–17 years with crowded and displaced teeth planned for non-extraction treatment were recruited from three orthodontic clinics. Participants were randomly allocated in a 1:1 ratio to treatment with either Damon Q ($n = 35$) or Victory ($n = 40$) using stratified blocks, with allocation concealed. EARR was assessed for all roots from incisors to molars using multiplanar reconstruction in cone beam computed tomography (CBCT) images acquired from various CBCT machines before, during and after treatment.

Results: Sixty-two patients were included in the EARR analysis. The upper incisors were the most affected tooth group, with mean EARR values of 0.20 mm for Damon and 0.51 mm for Victory (NS, alpha 1%). The frequency of clinically relevant EARR in this tooth group was 5.0% for Damon and 7.2% for Victory (NS, alpha 5%). Only one case with clinically relevant EARR after treatment was identified in the intermediate radiographic examinations.

Conclusions: The overall severity and frequency of EARR were below clinically relevant levels in both treatment groups. The results strengthen the evidence that routine intermediate radiography appears to be of limited relevance for early detection and prevention of severe EARR in non-extraction treatments for adolescents with crowded teeth.

Trial Registration: ClinicalTrials.gov: NCT05664282

1 | Introduction

External apical root resorption (EARR) is a common adverse effect of orthodontic treatment [1]. The upper incisors are the most affected tooth group, with EARR exceeding 2 mm in 10%–29% of cases [2]. The severity and frequency of EARR are influenced by various factors, including root shape deviations, the extent of tooth movement, high orthodontic forces and prolonged treatment durations [1, 3–5]. These factors contribute to variability in EARR among individuals, tooth groups and treatment methods, making prediction challenging [1, 3]. The close link between applied force, inflammation and EARR has spurred extensive research on force magnitude in orthodontics. Many of these studies, conducted on animals or extracted teeth, are difficult to extrapolate to clinical settings [6]. Orthodontic textbooks recommend light force [7, 8], and several studies have sought to identify the optimal force magnitude that maximises tooth movement while minimising adverse effects such as EARR. However, a recent systematic review found insufficient evidence to establish clear guidelines on the optimal force levels for minimising EARR [6].

Passive self-ligating bracket systems were developed to reduce frictional resistance and provide more physiological force levels [9, 10]. The Damon passive self-ligating bracket system, for example, is marketed with phrases like 'The light, gentle forces used by the Damon System promote efficient tooth movement and help improve oral health by preserving tooth roots' [11]. However, several systematic reviews, along with an overview of systematic reviews, have highlighted a lack of high-quality evidence regarding the impact of self-ligating brackets on EARR [1–4, 12–15]. Furthermore, a clinical study from 2018 using cone beam computed tomography (CBCT) found no difference in root volume loss when comparing the passive self-ligating Damon system with conventional Titanium Orthos brackets [16].

Based on studies with intraoral radiography [17, 18], an intermediate radiographic control after 6–9 months of treatment has traditionally been recommended in the orthodontic literature [7, 8]. Furthermore, if EARR ≥ 2 mm is detected, pausing active treatment for 2–3 months is advised to prevent further progression of EARR [17].

A subsequent study using CBCT, the preferred radiographic modality for research, did not confirm the effectiveness of early radiographic examination for detecting EARR, prompting the suggestion of a later examination at 12 months [19]. However, recent systematic reviews and clinical guidelines consider these recommendations to be weak [20, 21].

Most orthodontic treatments are performed during adolescence, with crowded teeth being the primary reason for seeking treatment. Therefore, this study focused on this age group and malocclusions.

The overall aim of this randomised controlled trial (RCT) was to evaluate EARR using multiplanar reconstruction (MPR) in CBCT examinations and to assess the relevance of intermediate radiographic examinations during non-extraction orthodontic treatments in adolescents with crowded and displaced teeth, treated with two standard fixed appliance systems.

- The primary objective was to compare the severity and frequency of EARR through CBCT examinations obtained at three points: before treatment, after levelling of the teeth and insertion of the first 0.019 × 0.025 stainless steel (SS) archwire and after treatment. This comparison was conducted using both passive self-ligating and conventional fixed appliance systems. In addition, the results were analysed in relation to the most affected tooth groups, total treatment duration, sex, initial irregularity of teeth and initial archwire dimensions.
- The secondary objective was to evaluate the relevance of intermediate radiography in detecting severe EARR.

Our primary hypothesis was that patients treated with passive self-ligating bracket systems would exhibit lower severity and frequency of EARR compared with those treated with conventional bracket systems. This hypothesis is based on theories suggesting that light forces reduce the risk of EARR, supported by previous studies. We further hypothesized that the upper incisors would be the most affected tooth group and that factors such as sex, initial irregularity of teeth and initial archwire dimensions would not influence EARR, while total treatment duration would. This hypothesis is based on previous studies. Our secondary hypothesis posits that the relevance of intermediate radiography is minimal, as the frequency of severe EARR is generally low in adolescent patients undergoing non-extraction treatment, consistent with prior findings.

2 | Materials and Methods

This study was part of the Crowded and Displaced Teeth (CROWDIT) project, which evaluates various outcomes of orthodontic treatments. The research question was framed using the Patient, Intervention, Comparator and Outcome (PICO) format, and the trial design was based on a tool developed for systematic reviews of adverse effects [2]. The trial reporting adhered to the Consolidated Standards of Reporting Trials (CONSORT) checklist.

2.1 | Trial Design and Ethics

This multicenter, two-arm, parallel-group, stratified block RCT used a 1:1 allocation ratio. The trial protocol and informed consent forms were approved by the Regional Ethical Review Board in accordance with the Declaration of Helsinki (Dnr. 2014/647) and by the Radiation Protection Committee in Region Skåne (SSFo2014-051) and Region Dalarna (2015-02-10). The protocol was registered on ClinicalTrials.gov with the registration number NCT05664282.

2.2 | Participants, Eligibility Criteria and Settings

Orthodontic treatments in this study were conducted at three specialist clinics: a university clinic, a Public Dental Service specialist clinic, and a private practice. Recruitment was carried out consecutively between 2016 and 2020 from the waiting list of

each clinic, consisting of patients identified by orthodontists as needing treatment with a fixed appliance under the free comprehensive dental care system for children and young patients in xxx. Follow-ups were completed in 2023.

Inclusion criteria:

- Ages 12–17 at the start of treatment
- Crowded and displaced anterior teeth in one or both arches
- Normal sagittal relation ± one cusp deviation
- Overbite ≥ 0 mm
- Normal or minor transverse dental discrepancy
- Treatment needs classified as 3, 4 or 5 according to the Index of Orthodontic Treatment Need (IOTN) dental health component [22, 23].

The exclusion criteria included treatment plans requiring extractions or surgical procedures; need for auxiliary appliances, such as transpalatal arch or Quad Helix; rheumatoid arthritis; missing permanent teeth; impacted teeth; prior orthodontic treatment; ongoing sucking habits; previous trauma to teeth or jaws with subjective, clinical or radiographic findings; periapical pathology; probing depth ≥ 5 mm at ≥ 4 surfaces of central incisors or first molars; visible plaque grade 3 [24] or communication difficulties.

2.3 | Randomization

The allocation sequence was computer-generated by a statistician, randomised into blocks of 10 and stratified by sex. Each clinic received sealed opaque envelopes containing an equal number of assignments for girls and boys. An orthodontist at each clinic provided eligible patients and their parents with oral and written information about the trial and invited them to participate. Once written assent from the patients and consent from their parents were obtained, the envelopes were opened by an independent staff member.

2.4 | Study Cast Baseline Analysis

The study casts were scanned to create three-dimensional models (O3DM, OrthoLab). DDP-Ortho software (version 2.10.2022) was used to record the IOTN grade [22, 23], Little's Irregularity Index [25], and overbite, overjet, sagittal and transverse relationships according to Björk [26].

2.5 | Treatment

The treatment goals were to achieve bilateral Class I sagittal relationships, normal vertical and transverse relationships and properly aligned teeth. Patients were randomised to one of two fixed appliance systems. One group received treatment with passive Damon Q brackets with 0.022 standard torque (Ormco Corporation, Orange, California, USA), bonded with Greengloo, with control intervals set at 8–10 weeks. Levelling and alignment were achieved using the following sequence of archwires: 0.014 (or 0.013), 0.018 CuNiTi and 0.014 × 0.025 (or 0.018 × 0.025) CuNiTi. The other group was treated with Victory low profile brackets, using APC Plus adhesive and a 0.022 MBT standard torque (3M, St. Paul, Minnesota, USA), with control intervals set at 6 weeks or longer. For this group, levelling and alignment were achieved using 0.016 archwires (preceded by 0.012 or 0.014 as needed) and 0.019 × 0.025 (or 0.014 × 0.025) heat-activated NiTi (HANT) archwires. In both groups, this was followed by 0.019 × 0.025 SS archwires. Variable torque adjustments and individual adaptations of bracket positioning, as well as bonding of bite raisers or disarticulation, were applied as needed in both groups.

The treatment protocols followed the guidelines of the manufacturer and were reviewed with all clinicians before the trial began. Three orthodontists, each with over 10 years of experience and familiarity with both bracket systems, performed the treatments.

2.6 | Outcomes

CBCT examinations were conducted at baseline (T0), after levelling and insertion of the 0.019 × 0.025 SS archwire (T1) and after treatment (T2) to assess EARR. Details of the CBCT devices, parameters and software are provided in Table 1.

All teeth from the incisors to the first molars were included in the CBCT field of view, and all roots were measured in millimetres, following the same sequence each time. Measurements were performed by an orthodontist with 18 years of experience who was not involved in the orthodontic treatments.

In accordance with the Guidelines for Reporting Reliability and Agreement Studies (GRRAS) [27], a pre-study was conducted to assess the reliability and agreement of the CBCT measurement method. Two raters evaluated inter- and intra-rater reliability and agreement for root length measurements; one of the raters was responsible for the measurements in the current study. This pre-study followed a protocol for measuring root length to ensure optimal visualisation of the root in the axial, coronal and sagittal planes, using MPR in CBCT examinations [28].

CBCT scans were excluded if the image quality was unacceptable. Individual roots were excluded if they were not fully visible in all three planes or if the image quality was insufficient, meaning that the tooth apex or the cementoenamel junction was not clearly visible on the mesial or distal root surface.

Root length was measured before (T0), during (T1) and after treatment (T2), with the severity of EARR calculated in millimetres. Based on previous studies [20, 29] and findings from a reliability and agreement study [28], a valid and clinically relevant cutoff for EARR was set at ≥ 2 mm. To categorise and report the frequency of EARR, Malmgren scores of 3 and 4 were used. Roots with ≥ 2 mm of shortening received a score of 3, and those with shortening of ≥one-third of the original root length received a score of 4 [30, 31]. Roots with EARR ≥ 4 mm or more than one-third root shortening were classified as having severe EARR [20]. Data on total treatment duration, time required for levelling and duration of 0.019 × 0.025 SS archwire use were obtained from patient records.

TABLE 1 | Radiological equipment and parameters used for CBCT examination.

CBCT machine	Radiological clinic	Orthodontic clinic	Number of examinations	Voltage (kV)	Tube current (mA)	Rotation (degrees)	Scan time (s)	FOV (cm)	Voxel size (μm)	Software	Monitor
3D Accuitomo 170 (Morita, Kyoto, Japan)	A	A	T0:10 T1:0 T2:0	80	3/6	360	17.5	8×8	160	i-Dixel, software, (Morita, Kyoto, Japan)	Barco View, MFGD, Belgium
Veraview epocs (Morita, Kyoto, Japan)	B	A	T0:18 T1:24 T1:27	80/90	2/3/5	180	9.3/9.4	8×8	125	i-Dixel software, (Morita, Kyoto, Japan)	Barco View, MFGD, Belgium
i-CAT 9140 (Envista holdings corp. California, US)	C	B	T0:34 T1:24 T2:11	120	5	360	4	8×16	300	Romexis software, (Planmeca Helsinki, Finland)	Barco View, MFGD, Belgium
Promax 3D Mid (Planmeca Helsinki, Finland)	C	B	T0:0 T1:2 T2:17	90	5	180	12	8×8	200	Romexis software, (Planmeca Helsinki, Finland)	Barco View, MFGD, Belgium
3D Accuitomo 170 (Morita, Kyoto, Japan)	D	C	T0:10 T1:10 T2:9	80	3	360	17.5	8×8	160	PACS, Sectra IDS7, (Sectra AB, Linköping, Sverige)	Barco View, MDCC-6330, Belgium

Abbreviations: CBCT, cone beam computed tomography; cm, centimetre; FOV, filed of view; kV, kilovolt; mA, milliampere; T0, before treatment start; T1, after levelling at insertion of first 0.019 × 0.025 stainless steel archwire; T2, after treatment; μm, micrometre.

2.7 | Missing Data

A per-protocol analysis was conducted, and attrition was analysed.

2.8 | Blinding

In view of the nature of the trial and treatment, neither trial staff nor patients could be blinded to the treatment type. However, the digital study models were coded and assessed blindly by an independent researcher. Although CBCT examinations were also coded, complete blinding of treatment type was not possible because the RCT groups could be distinguished by bracket design. Furthermore, blinding by timing was not feasible, as observers could discern whether teeth were crowded (T0), had brackets applied (T1) or were aligned (T2).

2.9 | Sample Size Calculation

Based on data from a previous study with a standard deviation (SD) of 1.0 mm for EARR [32], 23 participants per group were required to detect a 1 mm difference in EARR with a power of 90% and a 5% significance level (alpha).

2.10 | Statistical Methods

Data were analysed using SPSS software (version 25, SPSS, Chicago, Illinois, USA). Analyses were conducted for all roots, tooth groups (incisors, canines, premolars and molars), individual roots and patients. Data were checked for normal distribution, and mean differences in root shortening (mm) between the RCT groups were tested using an independent two-tailed *t*-test. To account for the risk of family-wise error, the alpha level for mean values was adjusted to 1%. For categorical data (clinically relevant EARR ≥ 2 mm or not), a chi-squared test was applied. Descriptive statistics were used to assess the relevance of intermediate radiography and to identify the most affected teeth or groups of teeth.

Multiple linear regression was performed to analyse whether EARR was influenced by the following variables: RCT group, total treatment duration (T0 to T2), sex, irregularity index of the upper incisors and initial archwire dimensions. The variables for treatment duration, irregularity index and initial archwire dimensions were dichotomized as follows: total treatment duration was categorised with a cutoff of 24 months; irregularity index was classified as mild/moderate or severe/very severe [25]; and initial archwire dimensions were set to 0.016 or 0.012–0.014. The mean EARR of the roots in the most affected tooth group served as the dependent variable.

For roots with EARR ≥ 2 mm at T2, remeasurements were conducted by an oral and maxillofacial radiologist with 5 years of experience. A consensus discussion with the observers followed to confirm actual root shortening or identify any measurement errors.

2.10.1 | Error of the Method

Inter- and intra-rater reliability and agreement for root length measurements of all teeth using MPR in CBCT were assessed in a pre-study involving repeated measurements of a subsample of 14 patients included in the current study. Before measurements were taken, the orthodontist conducting all measurements in the current study was calibrated through a multistep process with a specialist in oral and maxillofacial radiology. The pre-study showed that reliability and measurement error varied by time point and tooth group, with inter-rater intraclass correlation coefficient (ICC) ranging from 0.77 to 0.94 (95% confidence interval: 0.4–0.97) and intra-rater ICC ranging from 0.87 to 0.96 (95% confidence interval: 0.82–0.98). Measurement error for inter-rater agreement ranged from 0.52 to 0.77, whereas intra-rater agreement ranged from 0.41 to 0.66 [28].

3 | Results

3.1 | Participant Flow and Recruitment

A total of 75 patients were randomised, with final analyses conducted on 62 patients (30 in the Damon group and 32 in the Victory group), as shown in Figure 1. The attrition rate due to dropouts or missing CBCT examinations was low and comparable between the two RCT groups (14% for Damon and 15% for Victory). Baseline demographic and occlusal characteristics and treatment needs according to the IOTN are presented in Table 2.

3.2 | Treatment Duration

The overall treatment duration was 28.32 months (SD 7.90) for the Damon group and 25.06 months (SD 8.26) for the Victory group ($p = 0.099$). The time required to complete levelling, insert the first 0.019 × 0.025 SS archwire and perform intermediate radiography (T1) was 16.96 months (SD 6.99) for Damon and 13.82 months (SD 6.09) for Victory ($p = 0.056$). The duration from T1 to the end of active treatment (T2) was 11.12 months (SD 5.12) for Damon and 11.47 months (SD 6.92) for Victory ($p = 0.099$).

3.3 | Primary Outcome

The mean severity of EARR after treatment for the most affected tooth group (upper incisors) was low, measuring 0.20 mm for the Damon group and 0.51 mm for the Victory group. The differences between the RCT groups were generally small and not statistically significant. For the canine and premolar groups, the mean root length increased, suggesting ongoing root development (Table 3).

The frequency of clinically relevant EARR (≥ 2 mm) for all roots at T2 was 1.75% for Damon and 2.20% for Victory ($p = 0.468$). Of these, only one incisor in the Damon group showed EARR exceeding one-third of the original root length. For upper incisors, the frequency of EARR ≥ 2 mm was 5.0% for Damon and 7.2% for Victory ($p = 0.473$). No significant differences were observed between the Damon and Victory groups at either T1 or

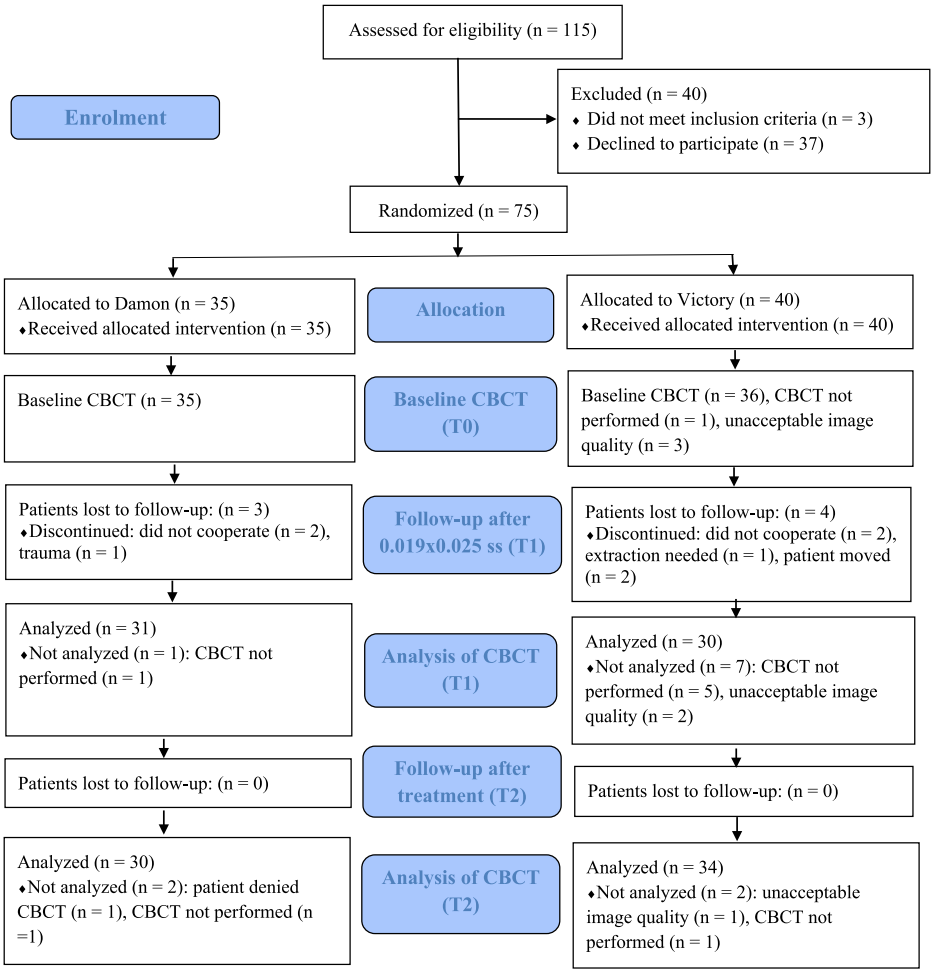

FIGURE 1 | CONSORT flow diagram. Of the 34 Victory patients who underwent CBCT at T2, two were excluded from the final analysis owing to poor image quality at T0. Abbreviations: CBCT, cone beam computed tomography; CONSORT, Consolidated Standards of Reporting Trials; T0, before treatment; T1, during treatment; T2, after treatment.

T2 (Figure 2). The proportion of patients with at least one root with EARR ≥2 mm was 23.3% ($n=7$) for Damon and 32.3% ($n=10$) for Victory ($p=0.437$; Table 4). Multiple linear regression was conducted to analyse whether the RCT group, total treatment duration, sex, irregularity index or initial archwire dimensions significantly predicted the mean EARR of the upper incisors. Negative values indicate root shortening. The fitted regression model was EARR = −0.44–0.00 × (RCT-group Damon) + 0.28 × (female sex) + 0.18 × (total treatment duration > 24 months) − 0.30 × (severe or very severe irregularity) − 0.00 × (initial archwire dimension 0.016). The overall regression model did not significantly predict EARR ($R^2=0.14$, $F=1.61$, $p=0.174$), indicating that none of the variables—RCT group, total treatment duration, sex, irregularity index of the upper incisors or initial archwire dimensions—significantly predicted the mean EARR of the upper incisors. The assumptions of the model were checked with the following tests and results: The multicollinearity test showed very low variance inflation factors (VIFs) < 1.258. In the residual plots, no signs of deviations from linearity or heteroscasisity were found. A test of normality of residuals according to Shapiro Wilk was NS ($p=0{,}226$). These results indicate that the model assumptions were not violated.

3.4 | Secondary Outcome

Of the 17 patients (41 roots) with EARR ≥2 mm after treatment (T2), only one root was identified as having EARR ≥2 mm at the intermediate radiography stage (Table 4; Victory patient 3, root 22). From T1 to T2, resorption for this root worsened only slightly, increasing from 2.48 to 2.93 mm (Table 4). The upper incisors were the most affected tooth group in terms of both severity and frequency (Tables 3 and 4; Figure 2).

3.5 | Harm

No serious harm or unintended effects were observed during treatment.

3.6 | Study Protocol

The complete study protocol is available in Swedish at all three clinics and can be provided upon request.

TABLE 2 | Baseline demographics and occlusal characteristics of the sample.

	Damon, $n = 35$	Victory, $n = 40$
Mean age in years (SD)	14.3 (1.7)	14.2 (1.7)
Sex boys/girls (*n*)	12/23	18/22
IOTN grade 3/4/5 (%)	26/71/3	27/73/0
Little's irregularity index mm upper mean (SD)	9.0 (3.4)	10.0 (3.5)
Little's irregularity index mm lower mean (SD)	5.7 (2.4)	6.4 (2.5)
Overjet mm mean (SD)	3.7 (1.9)	3.8 (1.4)
Overbite mm mean (SD)	4.1 (1.6)	3.4 (1.7)
Sagittal relation Class I/II/III (%)	49/51/0	55/43/2
Transversal relation normal/cross/scissors bite (%)	66/23/11	40/50/10
Inclination of upper 1 to NA mean (SD)	18.24 (9.3)	20.71 (7.0)

Note: No statistically significant differences between the groups ($p > 0.05$).
Abbreviations: *n*, number of patients; NA, nasion to A-point; SD, standard deviation.

4 | Discussion

The main finding of this study was that the severity and frequency of EARR were generally low in both RCT groups. Routine intermediate radiography to detect and prevent severe EARR appears to have minimal relevance and may be unnecessary for adolescents with crowded teeth undergoing non-extraction treatment.

The RCT design reduced the risk of selection bias and confounding variables. Patients with minor sagittal deviations corrected with intermaxillary elastics were included; however, the RCT design minimised the risk of bias in the results. The CBCT measurement method for assessing root length and EARR was thoroughly calibrated and evaluated for intra- and inter-rater reliability and agreement, yielding good results. The outcomes were assessed by a rater, who was not involved in the treatment to further minimise the risk of biased assessments.

A limitation of the multicenter design is the use of multiple CBCT machines. Although a quality assurance protocol was applied across all devices to standardise imaging parameters for optimal image quality relative to radiation dose, subjective assessments indicated marked differences in image quality between devices. This variation could potentially impact measurement results, although no significant differences in reliability were detected between devices [28]. Voxel sizes varied from 125 to 300 μm, introducing a potential bias. However, patients in the two RCT groups were evenly distributed across the four radiological machines, as confirmed by chi-squared tests (NS), supporting the robustness of results concerning the primary research question. Therefore, the difference in EARR between the two RCT groups should not be adversely affected. The inclusion of multiple caregivers and CBCT devices also enhances the generalizability of findings and facilitates comparisons with other studies.

Patients in this study received a higher radiation dose than routine patients. However, sufficient data were necessary to evaluate the need for routine radiographic examinations in these types of orthodontic treatments, which requires high-quality radiographic evidence for assessing EARR. Evidence shows that CBCT is superior to intraoral radiography for evaluating EARR, making CBCT the preferred choice for research purposes [33]. Nevertheless, conventional radiography, with its lower radiation dose, is recommended as the first choice for clinical purposes.

Detailed guidelines for reporting EARR are currently unavailable. Although root resorption is included in a recently developed core outcome set for routine orthodontic trials, specific guidance on evaluating and reporting outcomes—such as measurement type, scoring and tooth groups to be studied—is lacking [34]. The results of this study were presented as mean severity values (mm) and as EARR frequencies based on Malmgren scores, reflecting the challenges we encountered in synthesising results when conducting a systematic review on external root resorption [2]. Furthermore, results were provided for all roots, tooth groups, individual roots and at the patient level, which may facilitate comparisons with future studies.

A valid and clinically relevant cutoff for EARR was set at ≥ 2 mm, based on the absence of evidence suggesting that EARR < 2 mm impacts tooth health [35, 36]. Moreover, this threshold was supported by a reliability and agreement study, indicating that measurements below 2 mm may contain errors [28]. Analysis of clinically relevant EARR (≥ 2 mm) yielded non-significant differences between the RCT groups. Consequently, our primary hypothesis—that the Damon group would exhibit lower severity and frequency of EARR than the Victory group—was rejected, consistent with previous studies, reporting no difference in EARR frequency between the bracket systems [16, 32, 37, 38].

Minor, clinically irrelevant and statistically insignificant differences in mean EARR values were observed between the Damon and Victory groups. Mean EARR severity for the upper incisors was 0.20 mm for the Damon group and 0.51 mm for the Victory group, consistent with a recent systematic review, reporting mean values between 0.42 and 1.30 mm [4]. The frequency of EARR ≥ 2 mm for upper incisors in this study was 5.0% in the Damon group and 7.2% in the Victory group, lower than the 10%–29% range reported in a meta-analysis from another systematic review [2]. This difference may be attributed to the inclusion of extraction cases in previous studies assessing EARR of upper incisors. The upper incisors were the most affected tooth group in terms of both severity and frequency, consistent with earlier studies [1, 19]. Furthermore, the only root with EARR exceeding

TABLE 3 | Comparison of per-protocol mean EARR (mm) in Damon and Victory groups presented for all roots, tooth groups and individual teeth in the tooth group with the highest mean EARR (upper incisors).

Roots and tooth groups	Damon $n^a = 30$			Victory $n^a = 32$				95% CI of mean difference		
	n^b	Mean EARR T2	SD	n^b	Mean EARR T2	SD	Mean diff	Lower	Upper	*p*
All roots	1026	+0.04	0.97	1046	+0.05	1.11	0.00	−0.09	0.09	0.968
All incisors	240	−0.21	0.98	249	−0.35	0.93	−0.15	−0.32	0.02	0.091
All canines	*120*	*+0.31*	*0.93*	*123*	*+0.45*	*1.33*	*0.14*	*−0.15*	*0.43*	*0.334*
All premolars	*309*	*+0.02*	*1.01*	*307*	*+0.43*	*1.33*	*0.22*	*0.03*	*0.41*	*0.022*
All molars	357	−0.02	0.88	367	−0.14	0.74	−0.12	−0.24	−0.00	0.049
Upper incisors	120	−0.20	1.12	125	−0.51	1.03	−0.31	−0.58	−0.04	0.023
Lower incisors	120	−0.21	0.82	124	−0.19	0.78	−0.02	−0.18	0.23	0.825
Tooth 12	30	−0.16	0.98	32	−0.71	0.90	−0.56	−1.04	−0.09	0.021
Tooth 11	30	−0.44	1.48	31	−0.31	0.90	0.13	−0.50	0.75	0.685
Tooth 21	30	−0.10	1.05	31	−0.40	0.87	−0.30	−0.79	0.19	0.230
Tooth 22	30	−0.11	0.91	31	−0.62	1.37	−0.51	−1.11	0.08	0.091

Note: Tooth groups with negative EARR values indicate root shortening. Tooth groups with positive EARR values indicate increased mean root length. Tooth groups with increased mean root length in italics. *P*-value < 0.01 Statistically significant.
Abbreviations: CI, confidence interval; EARR, external apical root resorption; ITT, intention-to-treat; mm, millimetres; SD, standard deviation.
[a]Number of analysed patients in RCT group.
[b]Number of measured roots.

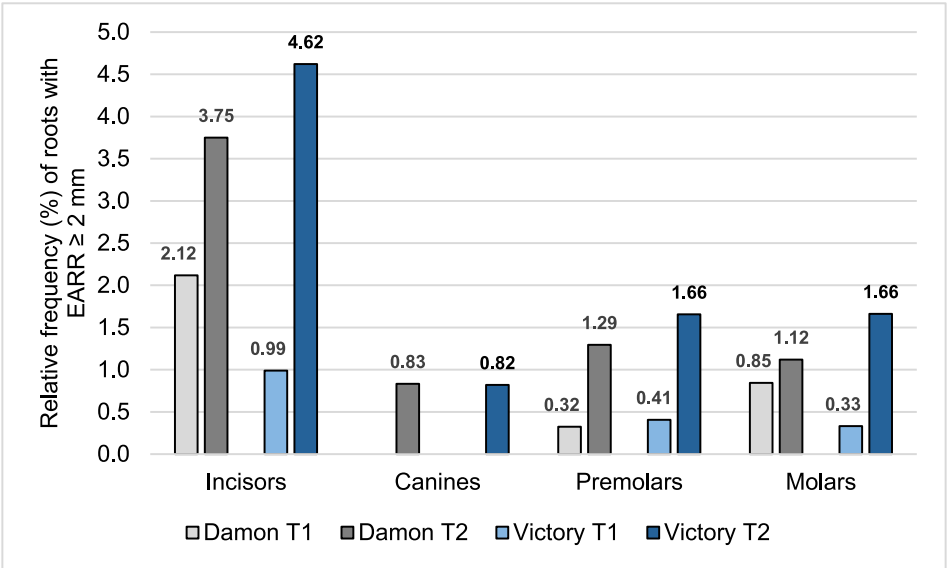

FIGURE 2 | Relative frequency of upper and lower roots with clinically relevant EARR (≥ 2 mm) in the Damon and Victory groups by tooth group at T1 and T2. Differences between groups were NS. Abbreviations: EARR, external apical root resorption; T1, intermediate radiography after levelling of teeth and insertion of the first 0.019 × 0.025 stainless steel archwire; T2, after treatment; NS, not statistically significant ($p > 0.05$).

one-third of the original root length (7.50 mm) was an upper central incisor. As with previous studies, these results showed mean root lengthening in canines and premolars, indicating ongoing root development in the age group studied. However, for roots still developing, assessing EARR relative to potential final root length remains challenging. The low severity and frequency of EARR, along with the finding that only one of the 41 roots with EARR ≥ 2 mm at the end of treatment (T2) showed signs of resorption at the intermediate radiographic examination (T1), support our secondary hypothesis that intermediate radiography is of limited relevance. This finding contrasts with earlier studies from the 1990s based on intraoral radiography [17, 18]. Clinical practice guidelines and a concomitant systematic review from 2020 provide only a weak recommendation for intermediate

TABLE 4 | All patients ($n = 17$) with ≥1 root with clinically relevant EARR (≥2 mm), classification of the severity of EARR according to the Malmgren score (score 3 or 4) [31] and EARR in millimetres at the end of treatment (T2).

	Incisors		Canines		Premolars		Molars	
RCT/ Patient	Root	EARR Score (mm)	Root	EARR Score (mm)	Root	EARR Score (mm)	Root	EARR Score (mm)
Damon								
1	42	3 (2.66)						
2	21	3 (2.39)			35b	3 (2.36)		
3	22	3 (2.36)					26p	3 (3.12)
4							26db	3 (2.06)
5					14p	3 (2.60)	16db	3 (3.26)
					24p	3 (2.38)	26p	3 (3.26)
6	12	3 (3.10)	43	3 (2.45)	44b	3 (2.49)		
	11	3 (2.19)						
	21	3 (3.09)						
	32	3 (2.70)						
	41	3 (2.39)						
7	11	4 (7.50)						
Victory								
1							16p	3 (2.04)
2			13	3 (2.06)				
3	12	3 (2.06)					46 mL	3 (2.31)
	22	**3 (2.93[a])**						
4	22	3 (2.87)			24b	3 (3.89)	26p	3 (3.53)
							36 mL	3 (2.14)
							46d	3 (2.59)
							46mb	3 (2.44)
5					24p	3 (2.35)		
6					15b	2 (2.38)		
7	12	3 (2.11)			14p	3 (2.10)		
	11	3 (2.37)			34b	3 (2.10)		
	21	3 (3.30)						
	22	3 (3.58)						
8	41	3 (2.10)						
9	22	3 (2.70)						
	41	3 (2.10)						
10	12	3 (2.14)						

Note: EARR score 3 or 4 according to Malmgren corresponds to ≥2 mm and >1/3 shortening of original root length [31].
Abbreviations: b, buccal; d, distal; db, distobuccal; EARR, external apical root resorption; mb, mesiobuccal; mm, millimetre; p, palatal.
[a]Text in bold is the one root identified as having the EARR score 3 at intermediate radiographic examination after insertion of the first 0.019 × 0.025 stainless steel archwire (T1).

radiography 12 months into treatment for extraction cases, based on consensus and limited evidence [20]. Another systematic review from 2020[2] found that studies using intraoral radiography to support intermediate radiography [17, 18] had a high risk of bias. However, a 2013 CBCT study by Makedonas et al. [19], which examined a single group of adolescents with

crowding treated with premolar extractions and conventional fixed appliances, did not confirm the relevance of intermediate radiography after 6 months and instead proposed a later assessment at 12 months; this study was considered to have a low risk of bias [2]. In our study, only one tooth with EARR ≥ 2 mm after treatment was identified by intermediate radiography. Further, only one tooth was identified with EARR ≥ 4 mm at the end of treatment. The low frequency of clinically relevant and severe EARR for the adolescents treated for crowding in the current study, in combination with the results of Makedonas et al., suggests that routine intermediate radiography, irrespective of modality, may be unnecessary for early detection and prevention of severe EARR (≥ 4 mm) in non-extraction cases without any known risk factors. This finding underscores the importance of basing radiographic examinations on individualised indications and minimising radiation exposure, according to the As Low As Diagnostically Acceptable (ALADA) principle [39]. Specific indications and risk factors may include anatomical root abnormalities, such as short, pipette-shaped or dilacerated roots, which may be associated with an increased risk of root resorption [5, 40].

The finding that EARR could not be predicted by treatment duration aligns with a clinical study by Makedonas et al. using CBCT [19] and three systematic reviews based on conventional radiography, all of which found weak evidence supporting an association between EARR and treatment duration [1, 3]. This suggests that the difference in treatment duration between the RCT groups in the current study is of minimal relevance. Considering the low severity of EARR observed in this study, the predictive value of potential confounders, such as treatment duration, sex, irregularity of the upper front teeth and initial archwire dimensions, is also low.

Long-term follow-up studies with a low risk of bias are needed [2]. Clinical studies suggest that EARR does not worsen after treatment [35] and that tooth mobility may increase when the remaining root length is less than 10 mm [36]. To strengthen the evidence on the long-term impact of EARR on tooth survival, the current study is designed and ethically approved to serve as a basis for extended follow-up.

5 | Conclusions

- The severity and frequency of EARR were generally low, with no statistically significant differences between the RCT groups.
- The difference in the proportion of patients with at least one root exhibiting clinically significant EARR (≥ 2 mm) was not statistically significant at 23.3% for the Damon group and 32.3% for the Victory group.
- The upper incisors showed the highest severity and frequency of EARR. Total treatment duration, initial irregularity of the upper incisors and sex did not significantly predict the severity of EARR in this tooth group.
- The results strengthen the evidence that routine intermediate radiography appears to have limited relevance for early detection and prevention of EARR in adolescents with crowded teeth undergoing non-extraction treatment. This finding aligns with the ALADA principle, emphasising the importance of individualised indications for radiographic examinations and minimising radiation exposure.

Author Contributions

Kristina Johansson substantial contributions to the design, acquisition, analysis and interpretation of data for the work including measurements of roots and statistical analyses. Drafting the work and revising it critically for important intellectual content. Final approval of the version to be published. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Helena Christell substantial contributions to the design, acquisition, analysis and interpretation of data for the work including statistical analyses. Drafting the work and revising it critically for important intellectual content. Final approval of the version to be published. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Anna Brechter substantial contributions to the design, acquisition and acquisition of data including treatment of patients. Drafting the work and revising it critically for important intellectual content. Final approval of the version to be published. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Liselotte Paulsson overall project leader for the CROWDIT project and overall RCT study. Substantial contributions to the design, analysis and interpretation of data for the work. Drafting the work and revising it critically for important intellectual content. Final approval of the version to be published. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Statement

The trial protocol and informed consent forms were approved by the Regional Ethical Review Board in accordance with the Declaration of Helsinki (Dnr. 2014/647) and by the Radiation Protection Committee in Region Skåne (SSFo2014-051) and Region Dalarna (2015-02-10).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the results of this study is available at The University of Malmö and can be provided upon request.

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