

Original article

Improved eruption path quantification and treatment time prognosis in alignment of impacted maxillary canines using CBCT imaging

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Summary

Background/objective: Orthodontic alignment of impacted upper canines is desirable for functional and aesthetic reasons, but time-consuming and difficult. Estimated treatment time is thus an important factor in treatment planning, its predictability based on hitherto available two-dimensional radiological measurements, however, quite limited (max. 39.1–42%). We thus aimed to improve treatment time prognosis of palatally impacted upper canines based on a three-dimensional quantification of eruption path length in baseline cone-beam computed tomographical (CBCT) diagnostic data.

Materials and methods: Baseline CBCT and orthopantomogram (OPT) data and treatment times of 30 adolescent non-syndromic/cleft orthodontic patients with an unilaterally palatally impacted upper canine, aligned by fixed orthodontic non-extraction traction treatment (closed eruption), were retrospectively analysed. Eruption path length was quantified by conventional two-dimensional and new three-dimensional methods, correlated with time to canine alignment and a prediction equation derived by linear regression.

Results: CBCT and OPT eruption path length and time to canine alignment did not show significant gender, age, or impaction side differences, but CBCT methods a distinct correlation ($r = 0.856/0.844$, $P < 0.001$) and high concordance [Lin's concordance correlation coefficient (CCC) = 0.9438]. Linear regression yielded a predictability ($r^2 \times 100\%$) of time to canine alignment from eruption path length of 73.3 per cent (CBCT trigonometry), 71.3 per cent (CBCT-simplified), and 50.0 per cent (OPT), respectively.

Limitations: The proposed model for treatment time prediction is only valid for eruption path lengths up to 8 mm. In some cases of canines being defined as impacted, these may have had the potential of spontaneous eruption. Possible inter-individual differences have to be considered.

Conclusions: Treatment time prediction for alignment of impacted upper canines can be achieved at an improved certainty of up to 73.3 per cent by the proposed CBCT methods for quantifying eruption path length compared to OPT measurements. Due to absence of gender, age, and impaction side differences, the derived regression formula should be universally usable in non-syndromic/cleft adolescents with palatally impacted upper canines.

Introduction

The upper permanent canines constitute the transition of the anterior to the posterior dental segment and are thus teeth of great importance both from a functional and aesthetical point of view (1). In general, the upper permanent canines erupt at 11 (boys) or 10.6 (girls) years of age (2). However, apart from third molars, they are the teeth most frequently impacted and dislocated with prevalence rates ranging from 1 to 3 per cent in the general population (3–6) with most impacted upper canines located in a palatal position (43–87%) (7). In orthodontic practices, the frequency of impacted upper canines is even higher, amounting up to 23.5 per cent (8, 9) with prevalence in women twice as high as in men (3).

Due to the importance of the upper canines, a conservative approach with orthodontic alignment of the impacted canine into the dental arch after surgical exposure and orthodontic traction is generally the desired treatment option (9, 10) without functional disadvantages (1), depending on the severity of impaction and the estimated risk of causing root resorptions at adjacent teeth during alignment, which is a possible side effect of this treatment option (9, 11). Alternative treatment options include surgical auto-transplantation (12) or removal of the impacted canine with reshaping of a persisting deciduous canine, orthodontic space closure or implantological prosthetic replacement (3).

Since orthodontic alignment of impacted canines is difficult and time-consuming and requires substantial treatment compliance by the patient (10, 13, 14), estimates of treatment necessity, difficulty, expected probability of success as well as expected treatment time are important criteria, when deciding on the best treatment option for the patient (13, 15). Available scientific investigations, however, which studied the eruptive prognosis of teeth, based on various metric and angular measurements in panoramic radiographs at baseline, first proposed by Dausch-Neumann (16) and Ericson and Kurol (17, 18), vary considerably in their results with only limited predictability achieved so far (8, 13–15, 19–23), probably due to the limitations of two-dimensional imaging.

In recent years, three-dimensional cone-beam computed tomographical (CBCT) imaging has found widespread acceptance and use in dental diagnostics due to reduced costs and increased information obtained. Although low-dose protocols for children become increasingly available (24), the radiation exposure is distinctly higher compared to conventional 2D radiological imaging, which requires a restrictive usage (25, 26), particularly in orthodontics with patients mostly adolescents during their main growth period. For diagnostics of impacted canines (25, 27), however, the benefits are generally considered to outweigh the additional risks. These comprise an exact determinability of canine location, angulation, and adjacent structures as well as bone and root resorptions (27–30), particularly in complex cases (31), possibly revealing contraindications for orthodontic alignment such as invasive cervical root resorption (ICRR) (32) and changing the originally intended treatment plan based on two-dimensional radiological records (33, 34).

Due to the increased clinical availability of CBCT baseline data in patient cases with impacted canines, we thus wanted to achieve an improved prediction of the time needed for alignment of a palatally impacted upper canine by traction treatment (closed eruption) based on the estimated eruption path length, quantified radiologically in three-dimensional CBCT images and compare its predictive reliability with previously published two-dimensional methods based on panoramic radiographs (OPT). Furthermore, we wanted to investigate, whether patient age at the start of treatment is associated with required treatment time and whether gender or

impaction-side-related differences exist regarding eruption path length or treatment time.

Materials and methods

Study design, setting, and participants

In this retrospective observational cohort study, data from 30 adolescent patients ($n = 30$; 18 female, 12 male) with an impacted upper canine, treated in a private orthodontic practice in the period from 2009 to 2016, were analysed. The study was conducted according to the principles of the Declaration of Helsinki (1964) and its later amendments as well as in accordance with the current ethical guidelines and the ALARA principle. The selection of patients, which were all treated by the same experienced orthodontist (M.S.), was based on the following inclusion criteria:

1. Adolescent patients up to and including 18 years of age and at the end of the late mixed dentition phase regarding their dental age at the start of orthodontic treatment, which had one palatally impacted upper canine, which was aligned in the course of treatment. Impaction at this dental developmental stage was defined as root formation completed to two thirds or more without tooth eruption in combination with angular tooth displacement resulting in an eruption path length of >6 mm, which—from clinical experience—required a surgical exposure due to spontaneous eruption being unlikely.
2. No preceding or ongoing orthodontic treatment at baseline examination.
3. Closed traction of the palatally impacted canine with the EWC® system (35, 36) (Adenta GmbH, Gilching, Germany) after surgical exposure and bonding of an attachment.
4. Non-extraction cases with initial total crowding in the upper arch ≤ 6 mm, according to orthodontic model analysis—i.e. no extraction of premolars to resolve crowding was performed during treatment.
5. Orthodontic treatment with a fixed orthodontic multi-bracket appliance.
6. Sufficient patient compliance by adherence to regular 4-week appointment intervals.
7. Successful alignment of the palatally impacted upper canine was achieved.
8. Complete patient diagnostic and treatment records available including a three-dimensional cone-beam computed tomogram (CBCT), taken for medical diagnostic reasons to assess the complex topographical situation for further treatment and the risk of root resorptions, within 1 year prior to the start of canine traction as well as complete available timeline and dates of diagnostic and treatment interventions.

Exclusion criteria were bilateral or buccal impactions of upper canines (determined by CBCT), congenital anomalies, and syndromes affecting the dentition and the craniofacial system including cleft lip and palate as well as documented systemic or local factors, which are known to influence bone metabolism and orthodontic tooth movement and thus alignment of the palatally impacted canine (endocrine or other chronic disorders, periodontitis, smoking, medication, radiation exposure etc.) (37–40).

Orthodontic treatment procedure for alignment of impacted upper canine

If a persisting deciduous canine was present, it was extracted at the start of orthodontic treatment. The SPEED System™ (Hespeler

Orthodontics Ltd., Cambridge, Ontario, Canada; anterior/posterior teeth 0.018"/0.022" slot) was used in treatment of all patients. Between start of treatment, which occurred after completion of initial diagnostics including CBCT imaging, and start of canine traction, an initial space management period of about 4–5 months occurred (molar tip-back uprighting and distalization, in some cases with a pendulum/beneslider, as well as premolar distalization by Class II elastics). After initial alignment with a 0.016" SPEED Supercable Twistflex (Hespeler Orthodontics Ltd.), an arch-bow sequence of 0.016" NiTi and 0.016" × 0.022" NiTi archwires (Highland Metals Inc., San Jose, California, USA) was used until a 0.016" × 0.022" stainless-steel arch-bow (Duradent™, Adenta GmbH) could be placed, which provided sufficient anchorage for canine traction. A passive closed coil spring (EWC® set, Adenta GmbH) encompassing the arch-bow between the lateral incisor and first premolar bracket minimized tipping of these adjacent teeth. A mucoperiosteal flap was surgically raised and the palatally impacted upper canine exposed up to the cemento-enamel junction (Figure 1A). Relative to the canine crown, bone was only removed at the palatal surface until it was completely exposed. No tunnel technique was applied. An EWC® traction appliance (14, 35, 36) (Adenta GmbH) was bonded to the canine via an attachment at the palatal surface and aligned in direction of the arch-bow used for anchorage purposes. Directly after bonding adhesive stability of the attachment was tested by momentarily applying a traction force of 1.5–2 N to the EWC® coil spring.

One week after flap repositioning and fixation—closed eruption, chosen for improved patient comfort and reduced after-bleeding and pain (41)—the coil spring was activated (Figure 1B) by 2 mm length reduction (0.32N), repeated every 4 weeks, and ligation to the arch bow 2 mm mesial of the first premolar bracket (disto-buccal traction). After eruption of the impacted canine, the spring was removed and further traction performed in buccal direction with an elastomeric power chain (Adenta GmbH, Figure 1C) until a buccal bracket for final levelling could be bonded, which was achieved with a segmental 0.016" SPEED Supercable Twistflex (Hespeler Orthodontics Ltd.) from the lateral incisor to the first premolar (Figure 1D), a 0.016" × 0.022" full-arch NiTi (Highland Metals Inc.) and subsequent rigid 0.017" × 0.025" beta-titanium (Trident™, Adenta GmbH) arch wires. Successful alignment was defined as achieved, when a 0.016" × 0.022" full-arch NiTi could be ligated without being vertically deflected at the canine. After canine alignment, fixed orthodontic treatment of remaining transversal, vertical, and sagittal malocclusions was performed (Supplementary Table 4).

Variables and data sources/measurement

From each blinded patient record available, we recorded the following variables for study purposes:

1. Patient gender (male/female)
2. Side of canine impaction (right—tooth 13/left—tooth 23)

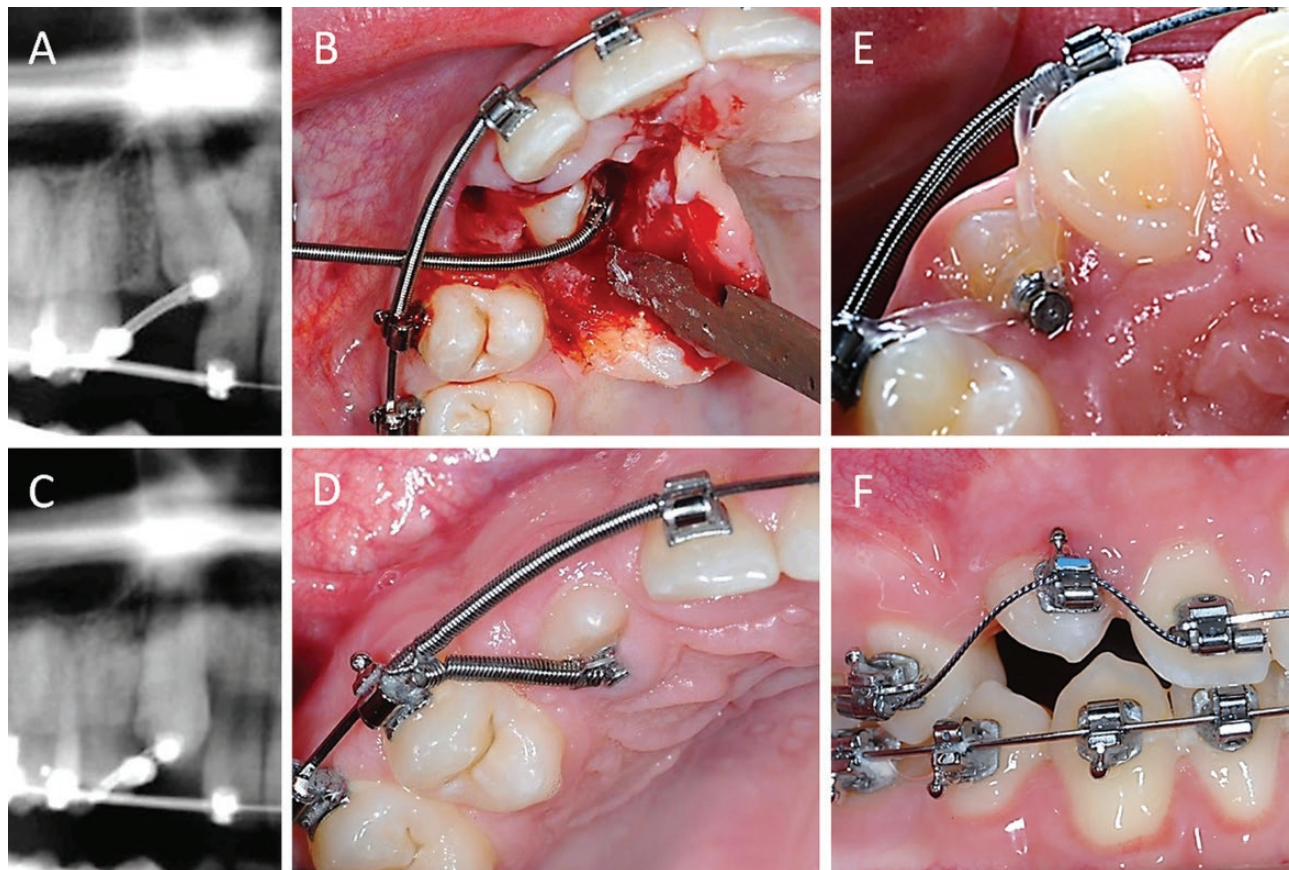


Figure 1. Successful alignment of an impacted upper right canine using the EWC® system (35) (non-extraction therapy). (A) Section of orthopantomogram and (B) clinical situation of surgical exposure (mucoperiosteal flap) and bonding of an oral button with the EWC® traction coil. (C) Section of orthopantomogram and (D) clinical situation of closed traction to the arch-bow, which was enclosed within a passive closed coil spring between the adjacent teeth for anchorage purposes, by means of a 2-mm-activated EWC® coil spring (0.32N). (E) Further buccal traction and derotation with an elastomeric power chain until a buccal bracket could be bonded. (F) Final extrusion and levelling by means of a segmental 0.016" SPEED Supercable Twistflex (Hespeler Orthodontics Ltd.) from the lateral incisor to the first premolar.

3. Dates of first traction coil activation and completed canine alignment
4. Patient age at first traction coil activation (years)
5. Time to alignment of impacted upper canine (months)
6. Total orthodontic treatment time (fixed treatment, months)
7. 3D-CBCT (trigonometric assessment): predicted eruption path length d (mm), calculated from the measured horizontal and vertical path components x and y
8. 3D-CBCT (simplified assessment): predicted eruption path length d (mm)
9. 2D-OPT: predicted eruption path length d (mm)

All CBCT radiographs were taken with a Master3DS Computerized Tomography System (E-WOO Technology Company Ltd., Korea) at an X-ray exposure of 90 kV and 3.5 mA (16×10 cm; T-Arch/AH/QH/FUL). Analysis of the three-dimensional CBCT datasets was performed twice by two different orthodontists (simplified analysis—M.S.; trigonometric analysis—C.K.) with the CBCT-manufacturer-provided viewer program EzImplant-CD-Viewer (version 1.5, INFINITT Healthcare Co. Ltd., Philipsburg, New Jersey, USA) for radiographs up to the year 2013 and with the program Ez3D2009-3D-CDViewer (version 1.2, Vatech Co. Ltd., Korea) for radiographs from 2013 onward, each set to default parameters (windowing value 'AutoFit', equalling hard-tissue view) and using the standard digital measurement tool for distances.

3D-CBCT trigonometric analysis of eruption path length

Since measurements in a defined (two-dimensional) plane of view reduce the actual three-dimensional eruption path to a two-dimensional projection hereof, the eruption path length (d) was determined within the three-dimensional CBCT radiographs by using a trigonometric, but clinically still usable approach. To this aim, we quantified the traversed horizontal (x) and vertical (y) movement components of the canine tip until alignment in an axial (x) and sagittal (y) CBCT plane as sides of a rectangular triangle (Figure 2A) and determined the actual eruption path length (d , hypotenuse) via the Pythagoras theorem according to $d^2 = x^2 + y^2$. The constructed predicted endpoint of the canine tip after alignment was defined via three auxiliary lines constructed within the CBCT in the area of the impacted canine (Figure 2B): the shortest distance between the lateral incisor and the first premolar adjacent to the impacted canine at the approximal contact point area (line 1), a tangent to the incisal edge of the lateral incisor and the buccal cusp tip of the first premolar (line 3) as well as a perpendicular line from the midpoint of line 1 to tangent 3 (line 2). The crossing point of lines 2 and 3 was defined as predicted ideal endpoint of the impacted canine tip at alignment.

To carry out the CBCT trigonometric analysis, we first rotated the CBCT dataset in coronal and axial planes until a coronal

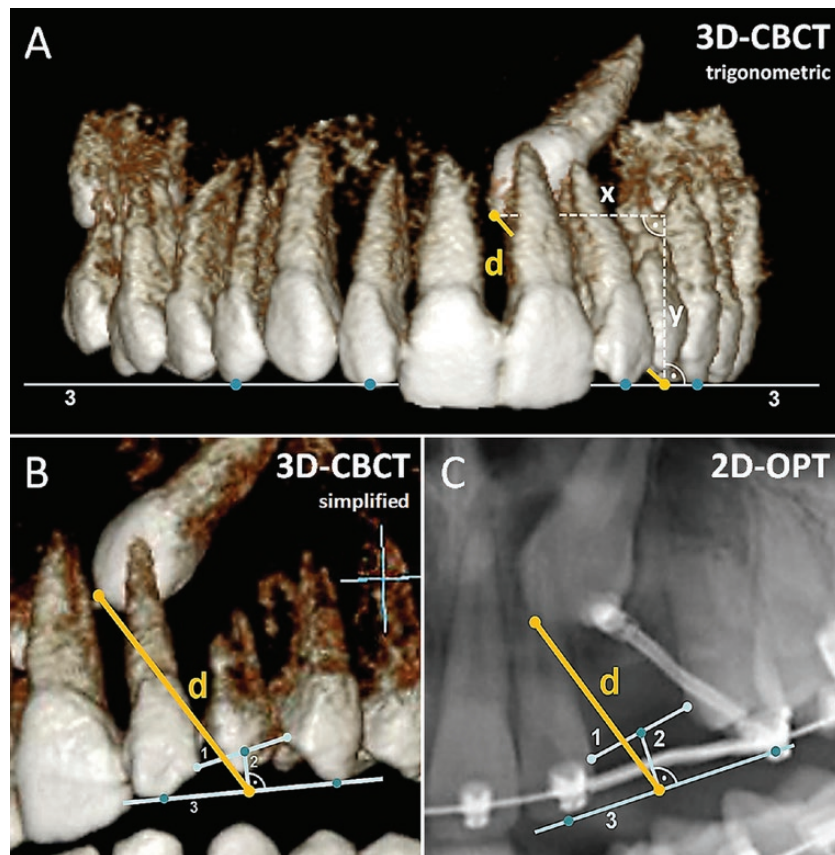


Figure 2. Measurement of eruption path length d , defined as distance from starting to endpoint of the canine tip as defined by three auxiliary lines, (A) by a trigonometric and (B) by a simplified clinical analysis in three-dimensional CBCT radiographs (cone-beam computed tomography) as well as (C) in OPT (orthopantomogram) radiographs: 1. shortest distance between lateral incisor and first premolar at the approximal contact point area; 2. perpendicular line from midpoint of line 1 to tangent 3 defines endpoint of the canine tip at alignment; 3. tangent (horizontal plane) to the incisal edge of the lateral incisor(s) and the buccal cusp tip of the first premolar(s). x/y = traversed horizontal/vertical distance of canine tip until alignment (sides of a right-angled triangle). For details please refer to the Materials and Methods section.

(Figure 3A) and axial (Figure 3B) plane could be selected passing through the buccal cusp tips of the first upper premolars. In this axial plane, the sagittal plane was then shifted to pass through the middle of the incisal edge of the lateral incisor at the side of the impacted canine (Figure 3B). After switching to this sagittal plane, the axial plane was rotated to be tangent to this incisal edge (Figure 3C) and its vertical position marked by introducing an auxiliary line with the measurement tool (Figure 3D). Returning to the axial plane (Figure 3E), an auxiliary line z was constructed with the measuring tool, connecting the buccal cusp tip of the first premolar and the distal lateral incisor edge (Figure 3F). In coronal plane, we then shifted the axial plane in vertical direction to the estimated approximal contact point location one-third of the crown height below the central fissure (Figure 3G). In this new axial plane, we determined the midpoint between the mesial first premolar and distal second incisor surfaces on auxiliary line z and marked this point with the measuring tool (Figure 3H). We then scrolled this axial plane vertically until the tip of the impacted canine became visible and shifted the sagittal plane to this tip (Figure 3I). We then adjusted the correct tangential position of the axial plane to the canine tip in the corresponding sagittal plane (Figure 3J). Within this axial plane through the tip of the impacted canine (Figure 3K), we connected the canine tip with the previously marked midpoint on auxiliary line z to quantify distance x , the horizontal movement component. Moving to the corresponding sagittal plane, we quantified distance y , the vertical movement component, by measuring the distance of the canine tip perpendicular to the previously introduced auxiliary line (Figure 3L).

3D-CBCT simplified analysis of eruption path length

In addition to the trigonometric analysis, we also quantified the predicted eruption path length (d) within the three-dimensional

CBCT radiographs by means of a simplified, clinically more accessible and less time-consuming assessment method (Figure 2B). To standardize the field of view for the CBCT measurement, the three-dimensional hard-tissue surface reconstruction of the CBCT jaw data was first positioned in direct frontal view of the skull with the occlusal plane and midsagittal plane parallel to the edges of the screen window and then rotated around the vertical axis to the side of the palatally impacted canine until the canine tip became visible and thus measurable between the opaque roots of the adjacent teeth. The eruption path length d was then measured as distance between the actual tip of the impacted canine and the constructed predicted endpoint of the canine tip after alignment as defined before (Figure 2B).

2D-OPT analysis of eruption path length

Apart from the three-dimensional quantifications based on CBCT data, we also applied a previously published OPT eruption path quantification and treatment time prognosis method as described by Schubert *et al.* (14) (Figure 2C) to baseline OPTs of the same patient collective, available from the referring dentist or taken as part of standard initial orthodontic diagnostic records, which allowed the primary diagnosis of canine impaction. These were manually traced and analysed (14) twice by the same orthodontist (M.S.) under standardized conditions. The eruption path length d was quantified as distance between the actual tip of the impacted canine and the constructed predicted endpoint of the canine tip after alignment as defined before (Figure 2C). The same OPTs were used to assess the dental age and development of a patient at baseline according to the method published by Demirjian *et al.* (42), based on mineralization stages (Supplementary Table 4).

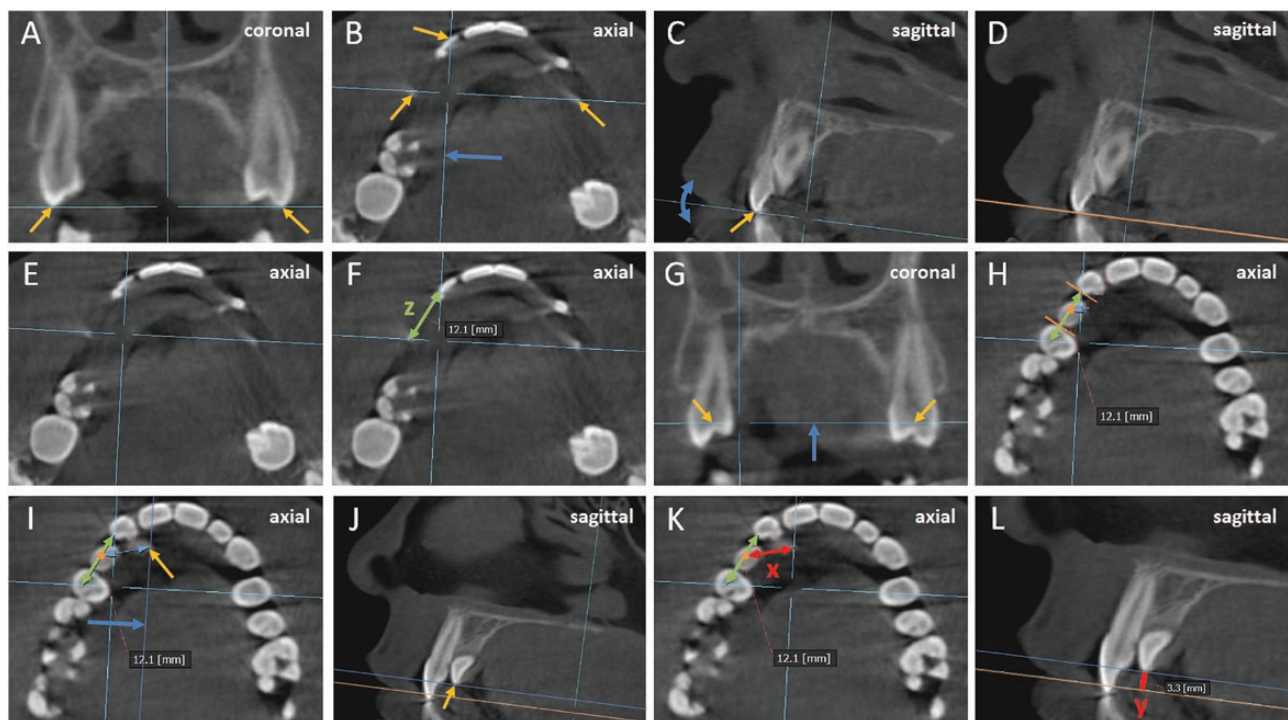


Figure 3. Exact trigonometric measurement of eruption path length d , defined as distance from starting to endpoint of the canine tip, in three-dimensional CBCT radiographs (cone-beam computed tomography) according to $d^2 = x^2 + y^2$ (Pythagoras theorem). x/y = traversed horizontal/vertical distance of canine tip until alignment (sides of a right-angled triangle). For details please refer to the Materials and Methods section. Blue arrows: shifting of planes; yellow arrows: points of interest; orange lines: auxiliary lines.

Bias

To assess intrarater reliability and reproducibility of measurements, all measurements were performed in triplicate for each respective procedure by the respective orthodontist with a time interval of at least 2 weeks between blinded measurements. To minimize bias, the triplicate mean was used for further analysis. In addition, orthodontic treatment of all patients was performed by the same experienced orthodontist (M.S.) and the researchers performing the radiological analyses of eruption path length (M.S., C.K.) were blinded to the time needed to canine alignment and the individual patient treatment timeline to avoid possible bias in measurements.

Study size

Study size was determined by the total number of patient records available meeting the inclusion and exclusion criteria. Sufficient statistical power was checked by an a priori power analysis for a bivariate correlation (two-tailed) of 'eruption path length' and 'time to canine alignment' considering a minimum coefficient of determination $r^2 = 0.391$ (effect size, previous study) (14) at an α -error of 0.05 (5%) and β -error of 0.1 (10%) yielding a minimum required sample size of $n = 19$ at an actual power of 90.8 per cent (G*Power 3.1.9) (43).

Quantitative variables and statistical methods

All statistical analyses were performed with IBM® SPSS® Statistics 22 (IBM, Armonk, New York, USA) and an online calculator for Lin's CCC (NIWA, <https://www.niwa.co.nz/node/104318/concordance>) by the same investigator (C.K.). For all continuous quantitative variables, we calculated the arithmetical mean (M) and the median (MD) with standard deviation (SD) and corresponding 95 per cent Bias-Controlled and accelerated (BCa) confidence intervals (CI, 1000 samples, robust bootstrapping procedure) as well as the corresponding minimum and maximum. Prior to analytical statistics, the requirements for parametric testing (normality, homogeneity of variance) were tested by Shapiro-Wilk and Levene tests as well as a visual histogram and zpred versus zresid plot evaluation. Due to possible violations indicated by these tests, non-parametric two-sided Mann-Whitney-U tests were used for intergroup comparisons (gender, side of impaction) of continuous variables. Associations between continuous variables were assessed by bivariate correlation and linear regression analyses (Pearson, two-tailed) with robust bootstrapped 95 per cent confidence intervals calculated for all coefficients with $r \geq 0.7/0.5/0.3$ interpreted as a strong/moderate/weak linear relationship. Concordance of 3D-CBCT simplified and trigonometric analysis of eruption path length was tested with Lin's CCC, a one-sample t test versus 0 (systematic bias) as well as a Bland-Altman analysis (bias and limits of agreement) with a CCC $\geq 0.95/0.9$ deemed substantial/moderate. Significance was set to $P \leq 0.05$. Intraclass correlation coefficients (ICC) (two-way mixed effects model, single measures) with 95 per cent confidence intervals were used to assess sufficient intrarater reliability of consecutive triplicate measurements, which was deemed substantial for ICCs ≥ 0.95 . A post hoc sensitivity analysis ($\alpha = 0.05$) for the bivariate correlation (two-tailed) eruption path length and time to canine alignment was performed to assess the minimally detectable effect size (r^2) at a power of 90 per cent from the study population ($n = 30$, G*Power 3.1.9) (43).

Results

Participants, descriptive, and outcome data

Of the 74 patients with an impacted upper canine available between 2009 and 2016, 44 had to be excluded according to the defined

inclusion/exclusion criteria (Figure 4). Three of these patients were over 18 years old, 12 had bilateral impactions of upper canines and in 29 cases the impacted upper canine was located buccally. A total of 30 patients, 12 male and 18 female, could be included in the study and were analysed (Figure 4, Supplementary Tables 1–4). Seven male (23.3%) and 8 female (26.7%) patients had an impacted right upper canine, whereas 5 male (16.7%) and 10 female (33.3%) patients an impacted upper left canine. Included patients were between 11 and 18 years of age at first activation of the traction coil spring (baseline) with a mean age of 13.8 years (SD = 1.7 years, Table 1). Further orthodontic baseline patient data is presented in Supplementary Table 4. None of the patients had anterior crowding and 11 of 30 patients had some posterior crowding as determined by orthodontic model analysis of plaster models.

Mean time to canine alignment was 11.8 months (SD = 5.3 months) with a mean total orthodontic treatment time of 20.1 months (SD = 7.5 months, Table 1). The corresponding mean eruption path length measured was 11.7 mm (SD = 2.8/3.2 mm) for both 3D-CBCT analyses and 15.0 mm (SD = 4.9 mm) for the OPT analysis (Table 1, Supplementary Tables 1–3 and Supplementary Data 1). Mean canine tip movement velocity during traction based on the measured eruption path length was 1.1 mm/month (CBCT, SD = 0.3/0.4 mm/month) and 1.4 mm/month (OPT, SD = 0.5 mm/month), respectively.

Main results

No significant gender-specific differences could be detected regarding the eruption path lengths measured by the two different CBCT ($P = 0.415/0.391$) or the OPT method ($P = 0.632$, Table 1), the time needed to achieve alignment of the palatally impacted upper canine (Table 1, $P = 0.819$) or total treatment time ($P = 0.325$). Furthermore, none of these measured variables showed significant differences regarding the side (left/right) of canine impaction (Table 1, $P \geq 0.461$). There was, however, a significant difference in patient age at first activation of the traction coil spring (Table 1, $P = 0.022$) with girls ($M = 13.2$ years, SD = 1.6 years) significantly younger than boys ($M = 14.6$ years, SD = 1.4 years).

A bivariate two-sided correlation of patient age at start of traction and time needed to canine alignment revealed no significant or distinct association of these two variables (Table 1, $r = 0.149$, $P = 0.432$). The time needed to canine alignment, however, correlated significantly and strongly with the measured eruption path length d , both in 3D-CBCT simplified ($r = 0.844$) and trigonometric ($r = 0.856$) analyses as well as 2D-OPT analysis ($r = 0.707$) (Table 2). The coefficients of determination r^2 of the corresponding significant ($P < 0.001$) linear regression models ranged from 0.713 for the simplified 3D-CBCT analysis to 0.733 for the trigonometric 3D-CBCT analysis and 0.500 for the 2D-OPT analysis (Figure 5; Table 2). Since gender and side of canine impaction had no significant effect on eruption path length, these variables were not included in the regression model. The linear regression allowed the formulation of a prediction equation, which permits the prediction of the time needed to canine alignment from the measured eruption path length d based on the regression coefficients determined for each measurement method (constant/ b , Table 2):

$$\begin{aligned} & \text{time to alignment of palatally impacted upper canine (months)} \\ & = \text{constant} + b \times \text{eruption path length } d \text{ (mm)} \end{aligned}$$

The regression model coefficient b can be interpreted as time needed for 1 mm of canine tip movement. Total orthodontic treatment time correlated (to a lesser degree) with the respective eruption path

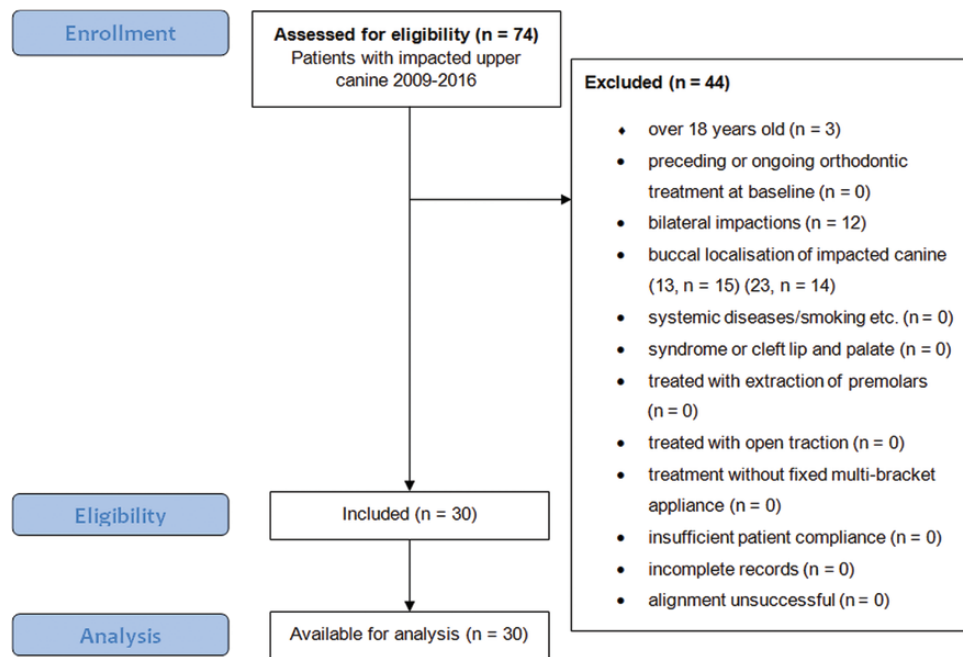


Figure 4. Flow chart of considered, excluded and included patients (STROBE).

Table 1. Descriptive and analytic statistics of measured parameters.

Measured variable (n = 30)	Mean (BCa 95% CI)	SD (BCa 95% CI)	Median (BCa 95% CI)	Min.	Max.	Δ Gender P (U/z)	Δ Side of impaction P (U/z)	Intrarater reliability ICC (95%CI)
Eruption path length <i>d</i> (mm) (3D-CBCT trigonometric analysis)	11.7 (10.8–12.8)	2.8 (2.1–3.2)	11.3 (10.3–12.4)	7.8	18.1	0.415 ^{ns} (88/–0.847)	0.653 ^{ns} (124/0.477)	0.997 (0.995–0.999)
Eruption path length <i>d</i> (mm) (3D-CBCT simplified analysis)	11.7 (10.6–12.9)	3.2 (2.4–3.8)	10.6 (9.8–13.3)	6.4	19.4	0.391 ^{ns} (87/0.889)	0.902 ^{ns} (116/0.145)	0.969 (0.944–0.984)
Eruption path length <i>d</i> (mm) (2D-OPT)	15.0 (13.3–17.1)	4.9 (3.6–5.9)	14.5 (12.4–16.8)	8.2	27.9	0.632 ^{ns} (96/–0.508)	0.653 ^{ns} (123.5/0.456)	0.999 (0.998–0.999)
Time to alignment of impacted canine (months)	11.8 (9.9–13.8)	5.3 (4.3–5.9)	10.0 (9.0–13.0)	3.0	24.0	0.819 ^{ns} (102.5/–0.234)	0.653 ^{ns} (124/0.479)	
Total treatment time (months)	20.1 (17.7–23.1)	7.5 (5.5–9.1)	19.0 (16.9–22.0)	7.0	43.0	0.325 ^{ns} (131.5/0.998)	0.461 ^{ns} (130.5/0.749)	
Patient age at first activation of traction coil spring (years)	13.8	1.7	14.0	11.0	18.0	0.022* (54/–2.326)	0.624 ^{ns} (100.5/–0.506)	

No significant differences regarding gender or side of impaction were found for eruption path length, time to alignment, total treatment time, except for patient age at activation with female patients ($M = 13.2$ years) younger than male patients ($M = 14.6$ years) at the beginning of traction treatment. Patient age did not correlate significantly with time needed for canine alignment. Correlation: patient age – time to alignment; $r = 0.149$ BCa; 95% CI (–0.188/0.471); $P = 0.432^{\text{ns}}$. BCa = Bias-Controlled and accelerated (1000 samples, robust bootstrapping procedure); CI = confidence interval; ICC = intraclass correlation coefficient; Min. = minimum; Max. = Maximum; n = number of subjects analysed; ns = not significant; P = significance level; r = Pearson's correlation coefficient; SD = standard deviation; U = test statistic of Mann–Whitney- U test; z = standardised test statistic.

* $P \leq 0.05$.

length d with $r = 0.361$ (BCa 95% CI [–0.082; 0.780], $P = 0.05$) for the simplified 3D-CBCT analysis and $r = 0.368$ (BCa 95% CI [–0.06; 0.807], $P = 0.046$) for the trigonometric analysis.

The concordance of the simplified and the trigonometric 3D measurements of the eruption path length d was moderate to substantial (Lin's CCC = 0.9483, Figure 5, Supplementary Data 2) with a non-significant ($P = 0.784$, one-sample t test versus 0) systematic measurement bias of 0.05 mm and 95 per cent limits of agreement of –1.92 and 2.02 mm (Bland–Altman analysis).

Other analyses

Intrarater reliability of eruption path length measurements was substantial for both 3D-CBCT and the 2D-OPT method of analysis with ICCs ranging from 0.969 to 0.999 (Table 1). A sensitivity analysis for the bivariate Pearson-correlation (two-tailed) eruption path length d and time to canine alignment at an α -error of 0.05 (5%) and β -error of 0.1 (10%) based on the finally available number of patient records ($n = 30$) determined a minimally detectable r^2 of 0.274 or r of 0.523, confirming sufficient study power.

Table 2. Regression model of eruption path length d (independent variable) and time to impacted canine alignment (dependent variable) for the three-dimensional simplified and trigonometric CBCT analyses as well as two-dimensional OPT analysis and prediction equation for time to alignment.

Linear regression eruption path length d — time to canine alignment	Regression model summary (ANOVA)						Parameters	
	r^2 (BCa 95% CI)	r (BCa 95% CI)	F	df_1	df_2	P	constant (BCa 95% CI)	b (BCa 95% CI)
3D-CBCT (simplified analysis)	0.713 (0.703†) (0.555/0.902)	0.844 (0.745/0.950)	69.479	1	28	<0.001***	-4.536* (-8.890/-1.921)	1.397*** (1.148/1.952)
3D-CBCT (trigonometric analysis)	0.733 (0.723†) (0.569/0.874)	0.856 (0.754/0.935)	76.736	1	28	<0.001***	-7.299** (-11.855/-4.278)	1.627*** (1.311/2.148)
2D-OPT	0.500 (0.482†) (0.298/0.728)	0.707 (0.546/0.853)	27.955	1	28	<0.001***	0.347 (-3.196/2.772)	0.762*** (0.536/1.158)
Prediction equation	Time to alignment of palatally impacted upper canine (months) = constant + $b \times$ eruption path length d (mm)							

b = regression model coefficient (can be interpreted as time needed for 1 mm of canine tip movement); BCa = Bias-controlled and accelerated (1000 samples, robust bootstrapping procedure); CI = confidence interval; CBCT = cone-beam computed tomography; d = distance from tip of palatally impacted canine to its predicted final position after traction treatment; $df_{1/2}$ = degrees of freedom (ANOVA); F = ANOVA test statistic; ns = not significant; OPT = orthopantomogram; P = significance level (ANOVA); r = Pearson's correlation coefficient; r^2 = coefficient of determination († adjusted, population); 2D = two-dimensional measurement; 3D = three-dimensional measurement.

*/**/*** $P \leq 0.05/0.01/0.001$.

Discussion

In our study, we aimed to develop an improved and more reliable method to predict the time needed for alignment of a palatally impacted upper canine by closed traction treatment based on eruption path length. Previously reported two-dimensional OPT methods of predicting time to canine alignment (dependent variable) from measured distances or angles (independent variables) (8, 13–15, 19–23) achieved a maximum coefficient of determination of $r^2 = 0.391$ (14) for an individual or $r^2 = 0.42$ (13) for combined measured parameters in linear regression analysis. In our own OPT analysis, based on an individual measured parameter (eruption path length), we achieved a slightly higher value of $r^2 = 0.500$. This means that 39.1, 42, or 50 per cent of the variance of treatment time could be previously explained by the variable eruption path length or a combination of measurements derived from two-dimensional OPT measurements, whereas 60.9, 58, or 50 per cent variance remain, most likely due to the inherent limitations of two-dimensional imaging as well as other individual exogenous or genetic patient factors (44, 45). Since the actual eruption path of the canine tip to its final position within the occlusal plane is three-dimensional by nature (16), a quantification using two-dimensional projections of this path with associated distortions (46), particularly in the canine region (18, 47), can only approximate the true path length.

As hypothesised, we found that predictability of treatment time for canine alignment could be considerably improved ($r^2 = 0.733$), if the eruption path was quantified by using a trigonometric approach in three-dimensional CBCT imaging with a conventional CBCT data viewer used for measurements. This means that as much as 73.3 per cent of the variance observed in treatment time could be explained by the three-dimensionally determined eruption path length according to the proposed trigonometric CBCT method, which is considerably more than achieved with conventional two-dimensional imaging (13, 14) with only 26.7 per cent variability remaining unpredictable.

Although the proposed new trigonometric CBCT method proved to be reliable, the complexity of measurements is rather time-demanding, limiting its clinical usability. Thus we also attempted to determine the eruption path length by a simplified method, only approximating the exact path, but still based on 3D-CBCT data.

Upon testing reliability and conformity of this less time-consuming method for clinical purposes, we found an only slightly reduced r^2 of 0.713 with systematic measurement bias negligible (0.05 mm) and moderate to substantial conformity (CCC = 0.94) with the trigonometric method. Limits of agreement, however, encompassed a range of about ± 2 mm, which means that in 95 per cent of patient cases with a palatally impacted canine the eruption path length measured by the simplified method may differ as much as 2 mm from the actual length. This indicates that for an individual patient the prognosis of treatment time is off by an additional $\pm 2 \times 1.6 = 3.2$ months ($b = 1.627$) compared to the trigonometric method, which should, however, be clinically acceptable.

Since the minimally recorded eruption path length in our study population was about 8 mm, a treatment time prediction for smaller eruption paths measured by any of the proposed methods, is not possible, since an extrapolation of linear regression beyond data limits is not reliable. Total treatment time also correlated with eruption path length, but to a lesser degree, since orthodontic treatment beyond canine alignment can vary considerably according to the individual malocclusions and anomalies present. Reliability and precision of CBCT-based interpretations regarding impacted canines is reported to be substantially higher than that of 2D-based interpretations (28–30), which is corroborated by the high ICC values obtained for both CBCT-based analyses of eruption path length, indicating substantial intrarater reliability.

Various previous studies have already attempted to predict treatment time to canine alignment in patients with impacted upper canines based on their degree of impaction derived from two-dimensional radiographs. Predictive variables measured as derived from two-dimensional radiological OPT records were canine angulation (long axis), displacement (vertical distance of canine tip from occlusal plane), antero-posterior position of the canine root apex relative to the midline, the degree of overlap of the adjacent incisor by the canine crown tip, and the horizontal mesio-distal canine position (8, 13–15, 19–23). Achieved predictability of these methods ($r^2 \times 100\%$) ranged from as low as 0.09 to 3 per cent for canine inclination (22, 23), 7.7 per cent for horizontal position (20) and from 0.36 per cent (23) over 18 per cent (13), 24 per cent (22) to

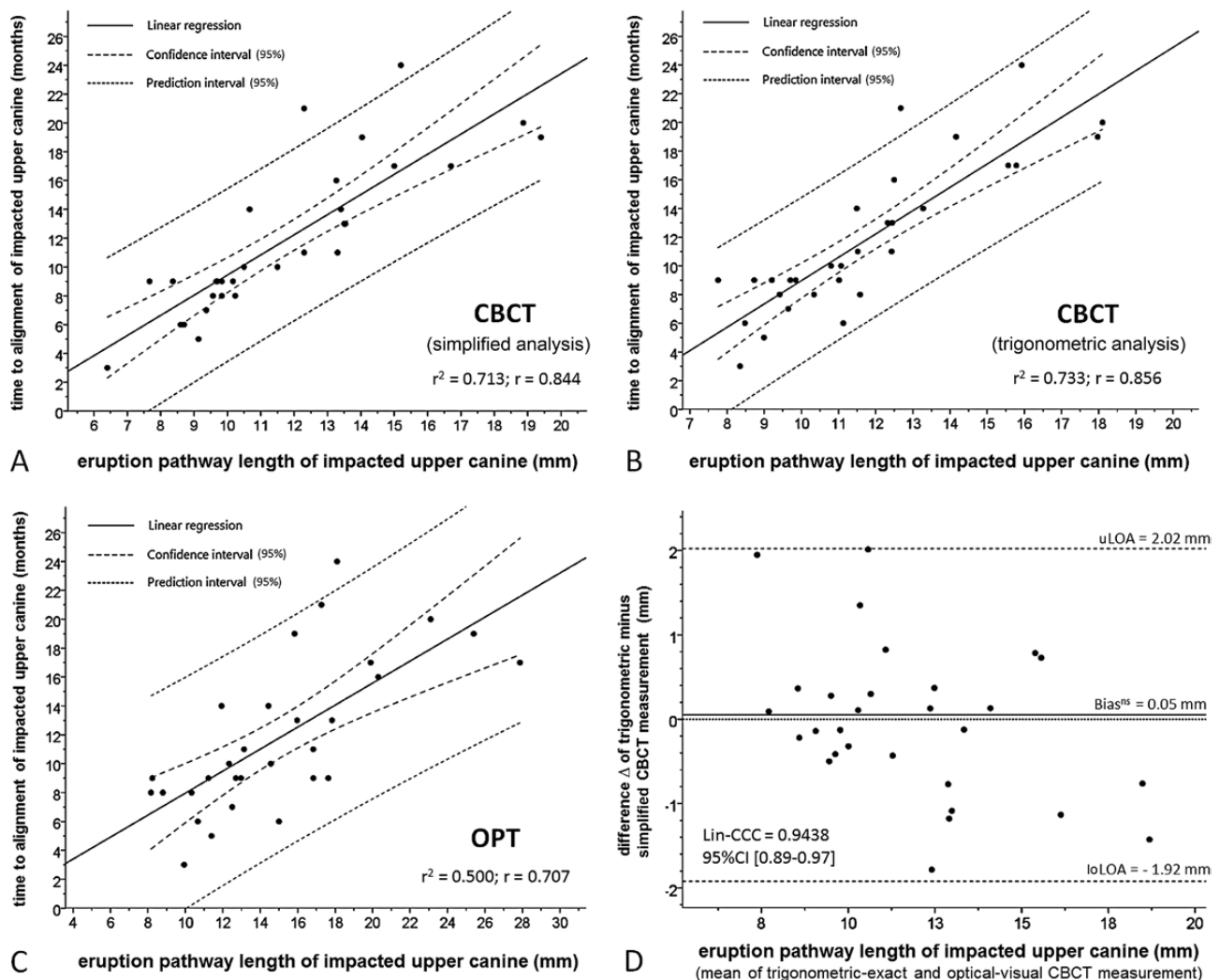


Figure 5. Linear regression analysis of eruption path length d (independent variable), as determined by 3D-CBCT simplified analysis (A), 3D-CBCT trigonometric analysis (B) and 2D-OPT analysis (C), and the time needed to achieve alignment of the impacted upper canine (dependent variable) with confidence and prediction intervals: 95 per cent of all patient measurements (population) are expected to fall within the prediction interval, whereas the confidence interval indicates the 95 per cent probability range of the linear regression line and equation. (D) Bland-Altman conformity analysis of 3D-CBCT simplified and trigonometric measurements. Bias = not significant (ns; $P = 0.784$; $T(29) = 0.276$; one-sample t test versus 0). Bias = systematic measurement error (Bland-Altman); CI = confidence interval; Lin-CCC = Lin's concordance correlation coefficient ρ_c ; uLOA/loLOA = upper/lower limit of agreement (Bland-Altman); r^2 = coefficient of determination (linear regression); r = Pearson's correlation coefficient.

39.1 per cent (14), and 50.0 per cent (own OPT data) for vertical distance measurements, which seems to be the predictability limit for two-dimensional radiological measurements. Zuccati *et al.* (15) reported a predictability of 42 per cent based on a combination of individual measured parameters as well as age. Some of these studies (13, 15, 20, 23) also evaluated impacted canines in vestibular position or bilateral impactions in patients of various age as well as implemented open traction of the canine. In contrast, we limited our analysis to singular palatally impacted canines in juveniles aligned by a closed eruption technique to ensure homogeneity of data, which also may have contributed to the higher predictability of time to canine alignment obtained.

Patient age at start of canine traction treatment was not significantly correlated with treatment time needed for canine alignment. This result indicates that within adolescents up to the age of 18 no age-related effects are to be expected regarding treatment time. Thus a start of canine traction treatment at an early age does not seem

to have advantages regarding the treatment duration. In adults, however, a treatment prolongation may be expected as indicated by Harzer *et al.* (10), Zuccati *et al.* (15), and Zhang *et al.* (48), whereas Baccetti *et al.* (19) also found no influence of age on the duration of traction and Stewart *et al.* (13) reported an even reduced treatment time with increasing age (up to 20 years), which might be explained by the fact that these authors focused on total treatment time instead of time to canine alignment.

As observed in previous studies (3), upper canine impaction was more frequent in women than in men. Gender and the side of the canine impaction, however, did not significantly affect treatment time or measured eruption path length. These results indicate that the severity of canine impaction does not seem to be gender-dependent nor does a preferred side for impaction of upper canines seem to exist. Thus these covariates did not need to be considered in the calculated regression models. Similar results were found by Baccetti *et al.* (19) and Fleming *et al.* (20), whereas other previous studies

found gender dependencies (14). The observed significantly higher age of girls at the start of traction treatment was most likely due to the generally earlier start of fixed orthodontic treatment in girls, who experience an earlier onset of puberty and reach the pubertal growth spurt maximum, used in orthodontic treatment, 2 years earlier than boys.

A limitation of this study is the fact, that inter-individual differences in tooth movement velocity could not be considered in the regression model. Although patients with known influences on orthodontic tooth movement velocity were excluded from the present study (37–40), existing genetic variability or local differences in bone density could not be controlled. From clinical experience, it has been known for some time that tooth movement in some patients occurs more rapidly than in others without predisposing factors present, thus giving rise to the concept of ‘fast movers’ and ‘slow movers’ (49). Possible explanations for these differences are genetic differences in cell metabolism or local anisotropy of bone (39, 44, 45), which probably account for the remaining 26.7 per cent variability in treatment time not explainable by the trigonometrically quantified eruption path length. To achieve improved predictability of treatment time, these factors as well as known influences of bone metabolism and tooth movement velocity will have to be investigated and considered in future studies to further improve predictability of treatment time in patients with palatally impacted canines. Furthermore in some cases of canines being defined as impacted, these may have had some potential of spontaneous eruption. We did, however, not want to take the risk of non-treatment and to incorporate canine alignment timewise into the otherwise necessary general orthodontic treatment due to other malocclusions.

Based on the chosen inclusion and exclusion criteria, our study results and the regression equation should be generalizable to all adolescent non-syndromic, non-cleft orthodontic patients up to 18 years of age with an unilaterally palatally impacted upper canine, but without known conditions influencing tooth movement velocity and bone metabolism, regardless of gender, impaction side, and age, if canine alignment is performed by fixed orthodontic non-extraction traction treatment (closed eruption) with good patient compliance.

Conclusions

Based on CBCT baseline data, a prediction of treatment time needed for alignment of palatally impacted upper canines can be achieved at a certainty level of up to 73.3 per cent by the proposed simplified and trigonometric CBCT methods for quantification of the estimated eruption path length, as defined by the movement of the canine tip until alignment. By contrast, distinctly lower certainty levels up to a maximum of 50.0 per cent are achieved based on a quantification of eruption path length in two-dimensional panoramic radiographs (OPT). Since no gender or side differences were found for treatment time or eruption path length, the determined regression formula should be universally usable in non-syndromic adolescents with palatally impacted upper canines irrespective of gender or impaction side. Regarding the treatment duration required for canine alignment, there seems to be no optimal time point for the start of canine traction up to 18 years of age.

Supplementary material

Supplementary material is available at the *European Journal of Orthodontics* online.

Conflict of Interest Statement

The authors report no financial or other conflict of interest relevant to this article, which is the intellectual property of the authors. Michael Schubert reports personal fees from Adenta GmbH (Gilching, Germany) outside the submitted work and holds a patent (102007048695) by the Deutsches Patent-und-Markenamt (Munich, Germany, 1 July 2010) for the EWC® traction system. Furthermore, no part of this article has been published before or is considered for publication elsewhere. It has been approved by all authors and the affiliated institution.

Data availability statement

All data are publically available either as supplementary information to this article or upon request.

Ethical statement

The study is in accordance with the ethical standards of the institutional and/or national ethics committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Since no diagnostic or treatment intervention on human subjects was performed for study purposes (retrospective evaluation of available, anonymized diagnostic patient records), no review/approval by an ethics board was required. Informed consent for the anonymized usage of patient data and records was obtained from all study participants.

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