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Treatment options for impacted maxillary canines and occurrence of ankylotic and resorptive processes: a 20-year retrospective study

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Abstract

Background This 20-year retrospective study aimed to evaluate the treatment methods used in patients with impacted maxillary permanent canines and to determine the occurrence of ankylotic and resorptive processes and their association with potential risk factors.

Methods The cohort consisted of 351 consecutive Caucasian patients (120 males and 231 females, mean age 18.4 and 19.9 years, respectively) with 420 impacted maxillary permanent canines. CT and CBCT findings were subsequently confirmed during surgery. Statistical analyses were performed by the generalized linear models, Pearson x^2 and Fisher exact tests using the statistical programs R and Statistica v. 14.

Results A total of 273 (65.0%) impacted canines were aligned in the dental arch by orthodontic traction after surgical exposure, this treatment was predominant in patients under 20 years of age. Surgical extraction was performed in 115 (27.2%) impacted canines and was more common in older patients. Ankylotic changes were recorded in 61 (14.5%) impacted canines. The probability of ankylosis increased with age, particularly after the patient's 20th year of life ($p < 0.001$). Patients were 1.2% likely to develop ankylosis at age 15 years, 4.3% at age 20 years, 14.1% at age 25 years, and 96.8% at age 45 years. Invasive cervical root resorption (ICRR) was found in 8 (1.9%) canines. In 4 canines (1.0%), root ankylosis in addition to ICRR was observed. In contrast to ankylosis, whose frequency of occurrence increased with age, the occurrence of ICRR resulting from PDL damage during surgery was more typical in younger patients. Canines in a high position above the root apices of the adjacent teeth, with a horizontal inclination of the longitudinal axis, with the crown located deep in the center of the alveolar bone and with labiopalatal position, should be considered critically impacted canines with a high risk to failure of orthodontic traction.

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Conclusion In conclusion, the treatment of impacted canines depends mainly on the age of the patient, and the position and inclination of the longitudinal axis of the impacted tooth. To select an adequate treatment method, we recommend CBCT examination, which allows a precise analysis of the position of impacted canines.

Keywords Ankylosis, Autotransplantation, CBCT, Impacted canines, Invasive cervical root resorption, Orthodontic treatment, Replacement root resorption, Surgical extraction

Introduction

The maxillary canine is one of the most important teeth in human dentition due to its dentofacial aesthetics and function. In Caucasians, the prevalence of maxillary permanent canine impaction ranges from 1 to 3.5% [1]. It is the second most commonly impacted permanent tooth after third molars [2]. Impacted and ectopically erupting canines can cause severe root resorption of adjacent teeth [3–5]. To confirm the clinical diagnosis of canine impaction, a panoramic radiograph is the image of first choice. Unlike conventional radiography, Cone Beam Computed Tomography (CBCT) allows accurate determination of the position and morphology of the impacted and adjacent teeth, the presence of ankylosis, and tooth resorption.

The primary objective of treating the impacted canine is to align it in the dental arch without causing any adverse effects on adjacent teeth and the canine itself. Treatment options for impacted canines include interceptive treatment (i.e. preventive extraction of primary canines, or primary canines and first molars, orthodontic opening of the space in the dental arch), and orthodontic alignment of the impacted canine after surgical exposure of the canine crown. If surgical exposure and orthodontic traction of the canine into the dental arch is considered difficult or impossible, autotransplantation or surgical extraction is the preferred method. Pathological conditions that restrict treatment options to surgical extraction include ankylosis, age-related replacement resorption, invasive cervical root resorption, and pre-eruptive intracoronal resorption.

Ankylosis

Ankylosis is defined as the pathological proliferation of a bone connecting two distinct mineralized structures that are normally separated from each other. Tooth ankylosis is characterized by an anatomical fusion of alveolar bone and tooth cementum. It can occur at any time during the eruption of a tooth, either before or after the tooth appears in the oral cavity [6].

Tooth ankylosis results in the loss of natural and orthodontic tooth movement. However, a tooth that does not respond to orthodontic forces by movement is not necessarily ankylotic. Biederman [6] considered three possible causes of ankylosis. A genetic or congenital gap in the periodontal membrane could perhaps explain ankylosis in unerupted teeth. Excessive masticatory pressure or trauma causing local injury to the periodontal membrane followed by ossification as a healing process could explain why primary molars are most commonly affected by ankylosis. He considered disturbed local metabolism as the most likely cause of ankylosis. Kurol and Magnusson [7] suggested that ankylosis is not a functional but a developmental disorder. Via [8] has pointed out the influence of heredity. Ankylosis or replacement root resorption may be one of the ways of healing injuries in which continuity of the periodontal ligament (PDL) has been lost, in cases of dental trauma, replantations, and autotransplantations [9].

The following clinical signs are typical for ankylotic teeth erupted into the oral cavity: An ankylotic tooth does not exhibit any mobility and may become infraoccluded. On tapping examination, it makes a high or sharp, solid sound, which is different from the dull, cushioned sound of a normal tooth [10]. Andersson et al. [11] suggest that the tooth mobility test and percussion test are conclusive if at least 20% of the root surface is affected by ankylosis. However, in cases of ankylosis of lesser extent and ankylotic impacted teeth, CBCT is a diagnostic option as it reveals obliteration of the PDL space.

The treatment options available for impacted ankylotic canines include surgical extraction and tooth decoronation. Surgical extraction may result in bone fracture or major bone loss, which can affect the quality of subsequent prosthetic treatment. For these reasons, the preferred alternative method is tooth decoronation. This procedure involves mucoperiosteal flap elevation and surgical removal of the tooth crown while the ankylotic root remains in place. The ankylotic tooth can be brought into the dental arch with a block of surrounding bone using the principle of distraction osteogenesis. However, this method may not be suitable for patients with ongoing growth in the vertical dimension, as it could compromise the outcome. Another treatment option is the surgical luxation of the ankylotic tooth, followed by orthodontic traction in the dental arch. Luxation breaks the bone bridges that cause ankylosis while keeping the tooth's vascular supply and innervation intact [6]. Orthodontic movement of the tooth after luxation allows healing of the periodontium. The desired outcome of this procedure is a functional tooth surrounded by healthy bone. After the surgery, antibiotic protection is necessary for 7–10 days to prevent any infection of the PDL. The method of choice is tetracycline as unlike amoxicillin, it not only reduces the risk of infection but also has an inhibitory effect on osteoclasts that cause tooth root resorption [12]. This procedure is also recommended by Proffit [13], who suggests that orthodontic force should be applied immediately after luxation to prevent re-ankylosis. Orthodontic forces should be reactivated every 10 days until the tooth is properly positioned in the dental arch [14, 15]. Tooth luxation may result in root or jaw fracture depending on the extent of ankylosis. Phelan et al. [16] recommend a localized ostectomy of the bone tissue at the site of ankylosis in cases where the ankylosis is located in the crestal area. Extraction and replantation of the ankylotic tooth, commonly reported in the literature, often result in loss of vitality and re-ankylosis [17]. Garcia [18] recommends this treatment method as the last possible effective option in cases where orthodontic traction has failed. To reduce inflammation and osteoclast activation after replantation, topical application of steroids (dexamethasone) is recommended [19]. Another treatment option is application of Emdogaine, which forms a matrix for fibrocyte development [17].

Age-related replacement resorption (AGRR) (Fig. 1)

According to Becker [20], a significant number of adults over the age of 40 experience a condition where their impacted canines do not move. This may be caused by sterile and non-inflammatory replacement resorption of the crown of these teeth. This condition is characterized by adhesions of degenerating follicular tissue remnants directly to the enamel of the impacted tooth, which causes the surface of the tooth to become disrupted by the resorption. When a tooth with a moderate degree of AGRR is surgically exposed, the soft tissues are very difficult to separate from the enamel surface, which may become pitted or dimpled. Teeth with this condition do not respond to orthodontic forces. In cases with more severe impairment, the enamel and dentin are resorbed by clastic cells. The tooth crown becomes more radiolucent and difficult to distinguish from the surrounding

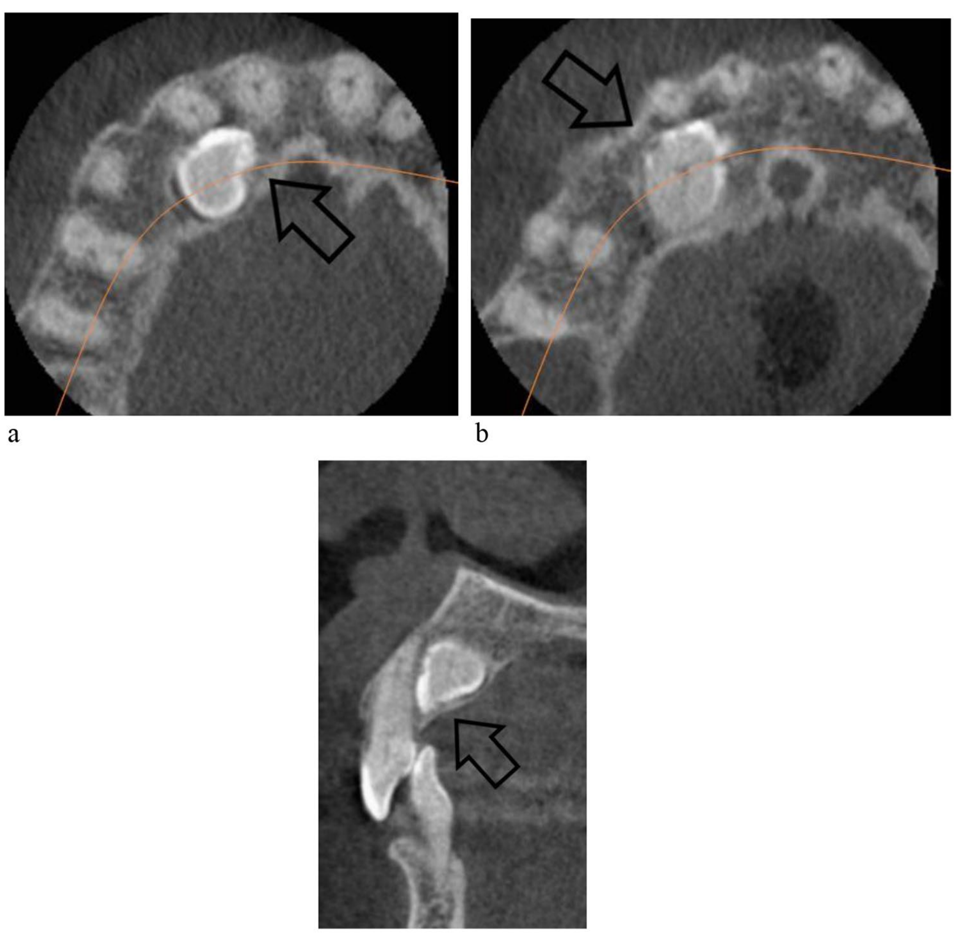

Fig. 1 Axial CBCT scans (**a**, **b**) and cross-sectional CBCT view (**c**) of a 54-year-old female with a right maxillary palatally impacted canine show age-related replacement resorption (AGRR). The invisible follicular sac around the crown of the canine, bone tightly adjacent to the enamel and a dimpled enamel surface are visible (black arrows)

alveolar bone. In extreme cases, the outline of the tooth becomes unclear on the radiograph. The tooth follicle disappears as part of age-related atrophy, which brings the enamel of the tooth into direct contact with the surrounding tissues. The tooth thus becomes incorporated into the surrounding alveolar bone and must be considered ankylotic. Garcia [18] refers to this type of disability as coronal ankylosis and considers it an absolute contra-indication to orthodontic movement.

Invasive cervical root resorption (ICRR) [20, 21] (Fig. 2)

ICRR is a rare, insidious, and aggressive form of external cervical resorption (ECR), also referred to in the literature as extracanal invasive resorption. It usually occurs when the PDL is damaged by hydrogen peroxide solution penetrating the dentin tubules during internal bleaching of non-vital teeth. This resorption process creates a typical ring around the neck of the tooth. A systematic review of pathophysiological mechanisms of root resorption after dental trauma was published by Galler et al. [22]. Heithersay [23] identified potential predisposing factors such as trauma (15.1%), intra-coronal restoration (14.4%), surgery (5.4%), and intra-coronal bleaching (3.9%). However, in many cases, no identifiable cause was found (16.4%). Patients with ICRR often report a history of orthodontic treatment (Heithersay −24.1%, Mavridou et al. −45.7%) [23, 24]. Becker [20] suggests that ICRR may be a reason why the tooth does not erupt or a contributing factor to treatment failure of impacted teeth. ICRR can be caused by surgical exposure of an impacted tooth in which the tooth is radically exposed beyond the cementoenamel junction (CEJ) or by testing tooth mobility by luxation movements. These practices can initiate the process of ICRR, which can take months or years to manifest. Excessive orthodontic forces can also trigger the onset of ICRR. The resorption process begins in the PDL, cementum, and dentin of the cervical part of the tooth root and eventually progresses deeper into the root dentin, potentially affecting the dental pulp. An impacted tooth may be mobile and yet not respond to orthodontic forces. The ICRR lesion represents a violation of the integrity of the PDL. In this region, an abnormal fusion of the ICRR lesion in the root dentin and the adjacent PDL occurs. These areas are not naturally able to respond to orthodontic forces and the processes of bone resorption and apposition that normally lead to tooth movement are

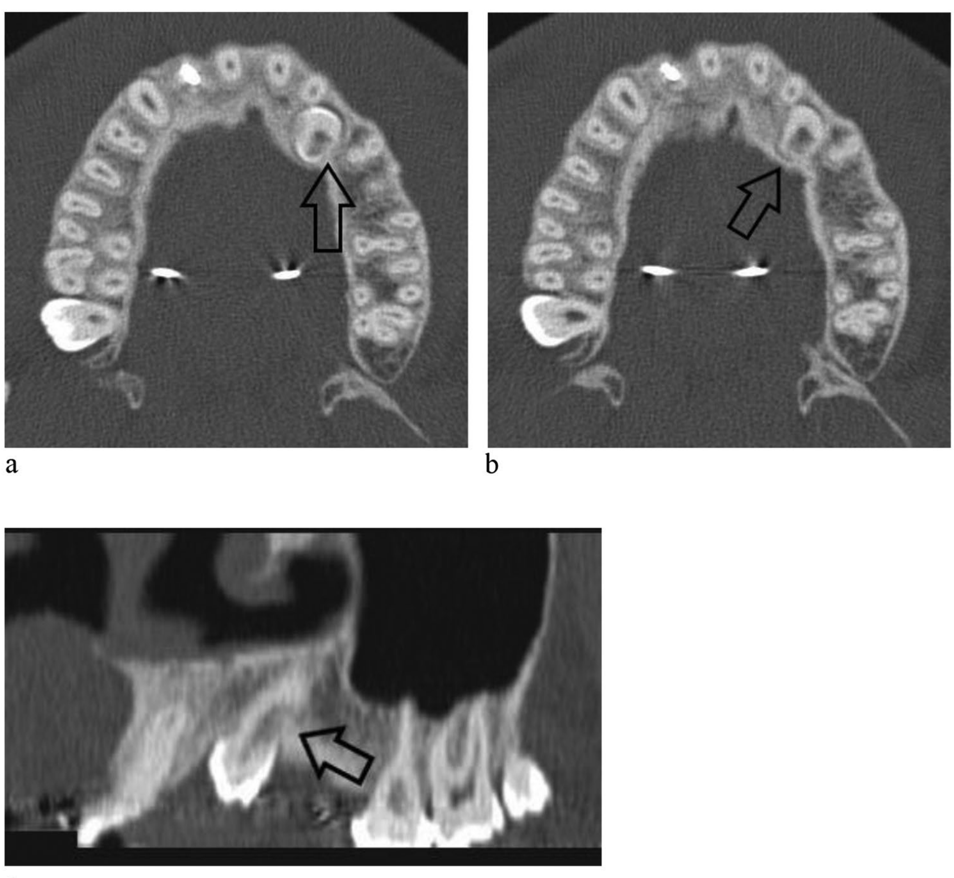

Fig. 2 Axial CBCT scans (**a**, **b**) and cross-sectional CBCT view (**c**) of an 18-year-old male with a left maxillary palatally impacted canine show invasive cervical root resorption (ICRR). An advanced resorption process is visible in the coronal half of the root on its distal aspect with a portal of entry (black arrows)

not activated. As the ICRR lesion enlarges, osteoid tissue grows into the resorption crater, creating an obstacle to tooth movement [25, 26]. Verification of the diagnosis of ICRR can be challenging as many of these lesions are located on the labial or lingual side of the root, which cannot be seen on plain X-ray films. However, when the X-ray is carefully evaluated, the "relative radiolucency" of the root is visible. This may appear as an atypical caries-like shadow, ballooning into the root dentin or undermining the enamel in the cervical region of the crown. The radiographic diagnosis of ICRR can easily be confused with "interproximal cervical burnout", which is often seen on periapical and bitewing radiographs. For a more accurate diagnosis, a CBCT examination can be conducted. The actual lesion can be clinically evaluated after uncovering the surgical flap. This procedure reveals the invasive nature of the process, which destroys the normal structure and integrity of the periodontium. ICRR is not the result of bacterial infection. As the name suggests, ICRR usually affects the cervical region of the tooth, close to the CEJ, but a similar lesion can occur anywhere on the surface of the root. A defective PDL allows clastic cells to come into direct contact with the root surface. The point where the cells begin to destroy the root surface is referred to as the "portal of entry" of resorption. From this point, resorption can spread deeper into the dentin coronally, apically, and circumpulpally, stopping only at the predentin layer surrounding the pulp [21]. The ICRR process can progress rapidly, leading to significant changes in the radiographic appearance of the tooth within a few months. If the resorption exceeds 20% of the dentin thickness, the tooth becomes very fragile and is indicated for extraction [28]. Therefore, early ICRR diagnosis and treatment is crucial. CBCT helps to confirm a diagnosis, locate access to the affected area, evaluate the extent of tooth destruction and residual mechanical resistance, assess the shape of the tooth root for possible autotransplantation, and examine the relationship between the tooth roots and adjacent teeth and anatomical structures [27]. If the tooth is strong enough, is surgically accessible, and the extent of ICRR is not too extensive, then curettage of the affected area and filling it with biocompatible material (Mineral Trioxide Aggregate - MTA, Intermediate Restorative Material - IRM) can be done. However, this procedure is rarely feasible.

Pre-eruptive intra-coronal resorption (PEIR) [20] (Fig. 3)

Many names are used in the literature to describe this unusual condition such as pre-eruptive dentine translucencies, penetrating crown resorption of an unerupted tooth, pre-eruption caries, occult caries, hidden caries, etc. As these names indicate, the condition is often confused by the authors with caries without regard to histopathological examination. This lesion was first described by Skillen in 1941 [28]. The prevalence of this abnormality in teeth is reported to be 0.2–27.3% in different countries [29]. Additionally, research shows that the lower second molars and second premolars are more frequently affected, and up to 31% of teeth are impacted [30, 31]. Becker [20] states that PEIR and ICRR probably have similar microscopic features and progress. The only difference is that ICRR enters through a gap in the cementum layer that covers root dentin, whereas PEIR affects the crown of an unerupted tooth, the point of entry can be a defect in the development of enamel resulting in imperfection in the integrity of the enamel. It usually appears as a tiny innocent-looking pinhole but can lead to the destruction of most of the crown of an unerupted tooth. The resorption process is sterile and asymptomatic, but when the tooth erupts into the oral cavity, the supply from the vascular plexus in the follicle is interrupted, causing the clastic cells responsible for the resorption to die. This can lead to a secondary infection with cariogenic bacteria. Unlike ICRR, teeth affected by

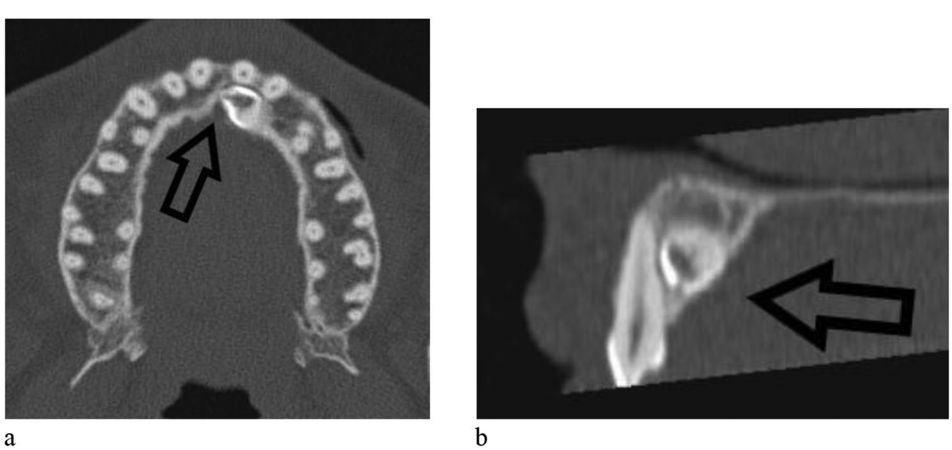

Fig. 3 Axial CBCT scan (**a**) and cross-sectional CBCT view (**b**) of a 33-year-old female with a left maxillary palatally impacted canine show pre-eruptive intra-coronal resorption (PEIR) with a typical pinhole lesion (black arrows). Large, radiolucent, crown-destructing intracoronal resorption is visible

PEIR can still erupt because they have an intact PDL. However, it is not uncommon for teeth with this condition to remain impacted.

This study aimed to evaluate the treatment methods used for the impacted maxillary permanent canines and to determine the prevalence of ankylosis, AGRR, ICRR, and PEIR. The study also aimed to examine the association of the above pathological changes with the age and sex of the patients and the position of the impacted canine.

Materials and methods

The retrospective study analyzed data from patients who visited the first author (P.C.) of the article for diagnostics, determination of the treatment plan, and implementation of orthodontic treatment, if indicated, between 2003 and 2023. The initial sample, a set of 387 patients with impacted maxillary permanent canines, was collected. Patients were excluded if they had a history of dento-alveolar trauma, genetic syndromes, or metabolic disorders (such as cleft lip and/or palate, dysostosis cleidocranialis, hypothyroidism, hypopituitarism), oligodontia, missing records, insufficient quality of radiographs and CBCT scans, or if they did not complete the treatment.

CBCT examination for accurate diagnosis and planning of impacted canine treatment was performed before and during orthodontic treatment. During this period, spiral CT scanner Mx8000 (Philips, Eindhoven, The Netherlands; scan parameters – matrix size of 768×768, pitch 0.875, 120 kV, and 100 mAs) and 2 CBCT systems: iCAT (Imaging Sciences International, Hatfield, PA, USA; scan parameters – 120 kV, 5 mA, voxel size 0.3 mm, exposure time 7 s)) and Dental Imaging Equipment and software CS 9300 C (Carestream Dental LCC, Atlanta, USA; scan parameters – 90 kV, 4 mA, voxel size 180 µm, scan time 8 s) were employed. The cone beam generated DICOM files were imported into iCATVision software and OnDemand 3D software, resp. Trophy Dicom 6.4.0.4 (Kodak) and CS 3D Imaging.

The following data were recorded: patient's age at the beginning of therapy, sex, type of impaction (unilateral, bilateral), and the affected side. The position of the canine in relation to the dental arch was assessed as palatally impacted canine (PIC) or buccally impacted canine (BIC) if more than half of the crown was palatally or buccally impacted from the middle of the alveolar bone, centrally (CIC) if the crown was located in the center of the alveolar bone, labiopalatally impacted canine (L-PIC) if the canine lied labially to the lateral incisor and the tip of the canine crown extended palatally beyond the central incisor [32]. Further, the following parameters were evaluated: position of the crown tip of the impacted canine in the vertical plane (at the level of the cervical, middle or apical third of the root of the adjacent incisor and above the apices of the adjacent teeth), inclination of the longitudinal axis of the impacted canine (mesial, vertical, distal, horizontal, palatal), presence of transposition (no transposition, complete transposition with lateral incisor, complete transposition with first premolar), presence of ankylosis (no ankylosis, ankylosis diagnosed by CBCT examination before treatment and confirmed at surgery, ankylosis diagnosed by CBCT examination after failure of orthodontic canine traction and confirmed at surgery, ankylosis occurring after autotransplantation), presence of ICRR (no ICRR, ICRR diagnosed by CBCT examination before treatment, ICRR diagnosed at failure of orthodontic traction, ICRR occurring after tooth autotransplantation), type of ankylotic or resorptive process (no pathology - intact PDL space, root ankylosis (RA) – invisible PDL space, ICRR, PEIR, AGRR, RRR (replacement root resorption - invisible PDL space and presence of tissue replacement of the root (Fig. 4)), treatment method (orthodontic traction after surgical exposure of the crown without extractions and with extractions of other permanent teeth, surgical extraction of impacted

Fig. 4 Axial CBCT scans (**a**, **b**) of a 16-year-old male with a right maxillary palatally impacted canine show idiopathic replacement root resorption (white arrows)

canine, surgical extraction due to failure of orthodontic traction, autotransplantation, spontaneous canine eruption after preventive measures, i.e. after extraction of a primary canine and/or opening the space in the dental arch, rejection of treatment by a patient).

Radiographic analysis

CBCT images were assessed by two independent assessors (authors P.C. and C.C). In controversial cases, the assessment was repeated and discussed to reach a consensus. All data were anonymized and recorded in an Excel spreadsheet.

Statistical analyses

Standard descriptive statistics applied in the analysis included absolute and relative frequencies for categorical variables and mean with standard deviation (SD) or median with quartiles for quantitative variables. To compare different groups that are not related, we used one-way analysis of variance (ANOVA) and Kruskal–Wallis tests to compare continuous variables. For the comparison of categorical variables, Pearson x^2 analysis or Fisher exact tests were applied. The value of $P<0.05$ was considered statistically significant. These statistical analyses were performed using Statistica version 14 (StatSoft Inc, Tulsa, Oklahoma, USA).

In addition, generalized linear models (GLM) were utilized to analyze the occurrence of ankylosis in terms of its presence or absence, assuming binomial error distribution and logits as a link function. As predictors, the following variables were included in the models: age of patients, sex, the position of the tooth crown to the dental arch (buccal, central, palatal, and labiopalatal), the position of the crown tip of the impacted canine in the vertical plane to the root of the adjacent tooth (at the level of the cervical third of the adjacent tooth, at the level of the middle third, at the level of the apical third, above the apices of the roots of the adjacent teeth), the inclination of the longitudinal axis of the impacted canine (mesial, vertical, distal, horizontal, palatal), and transposition (no transposition, complete transposition with lateral incisor, complete transposition with the first premolar). We initially applied single-factor models, then the set of combined models using forward/backward selection. The best model most supported by data was selected based on a difference in Akaike´s Information Criterion (ΔAICc) greater than 2, following the method proposed by Burnham and Anderson [33]. Subsequently, the sample of 56 canines showing the presence of ankylosis was studied. To assess the effects of categorical variables such as sex, type of impaction (unilateral, bilateral), side of impaction (right, left), position of the crown to the dental arch, position of the crown tip, and inclination, we used the chi-squared test of goodness-of-fit. If the null hypothesis (H0) regarding equal representation of all categories was not rejected, we calculated the minimum sample size (MSS) that would be required to achieve a power of 80% for the observed effect size. Subsequently, we added another seven canines to the sample, which had developed ankylosis during the therapy or transplantation ($n=63$). This enriched sample was then subjected to the same statistical tests as described earlier. These statistical analyses were conducted using the statistical program R [34]. To calculate the chi-squared test, the package AMR [35] was adopted. The MSS was estimated using a method implemented in the pwr package [36].

This study follows the principles of the Declaration of Helsinki. All patients (and a parent in patients under 18 years of age) signed an informed consent that their radiological findings (without disclosing their identities) may be used for future research into maxillary canine impaction. The Committee for Ethics of St. Anne´s University Hospital Brno, Czech Republic (Approval no. 01G/2020) approved the study.

Results

Thirty-six patients were excluded from the initial sample set based on exclusion criteria such as incomplete records (17), insufficient quality of CBCT scans (12), dysostosis cleidocranialis (4), cleft (1), and unfinished orthodontic treatment (2). Finally, the retrospective study cohort included 351 consecutive Caucasian patients with a mean age of 19.4±9.6. The cohort comprised 120 males (34.2%) and 231 females (65.8%). The age range for males was 10.5 to 59.5 years (median 15.29, SD 8.5), and for females 10.16 to 64.33 years (median 15.5, SD 10.06). The male-to-female ratio was 1:1.9. A total of 420 maxillary permanent canine impactions were detected in these patients, with 69 (19.7%) patients having bilateral impactions and 282 (80.3%) having only unilateral impactions. In individuals with unilateral impaction, we observed impaction on the right and left sides in 132 (46.8%) and 150 (53.2%) cases, respectively. We found palatal and buccal position of the crown in relation to the dental arch in 267 (63.6%) and 42 (10%) impacted canines, respectively, and in the central position in 104 (24.7%) and labiopalatal position in 7 (1.7%) canines. The position of the crown tip of the impacted canine in the vertical plane was at the level of the cervical third of the root of the adjacent tooth in 205 (48.8%) canines, at the level of the middle third in 144 (34.3%) and at the level of the apical third in 43 (10.2%). Twenty-eight (6.7%) canines were in a high position above the apices of the roots of the adjacent teeth. The vast majority of 350 (83.3%) impacted canines had a mesially inclined longitudinal axis. Forty-two (10%) canines had vertical, 1 (0.25%) distal, and 1 (0.25%) palatal inclination. In 26 (6.2%) cases, we evaluated the horizontal position of the impacted canine. A majority (17 of

Table 1 Treatment methods for impacted canines according to the position of the impacted canine crown in the vertical plane and the inclination of its longitudinal axis (column treatment method: 1 - orthodontic alignment after surgical exposure without extractions of other permanent teeth, 2 - orthodontic alignment after surgical exposure with extractions of other permanent teeth, 3 - surgical extraction, 4 - surgical extraction after failure of orthodontic traction, 5 - autotransplantation, 6 - spontaneous canine eruption after preventive procedures, i.e. extraction of the primary canine and/or orthodontic opening of the site, 7 - refusal of treatment by the patient)

Inclination of the longitudinal axis of the impacted canine		Mesial inclination	Vertical inclination	Distal inclination	Horizontal inclination	Palatal inclination	Total
Position of the impacted canine crown in the vertical plane	**Treatment method**						
Cervical third of the adjacent tooth root	1	132	12	0	0	0	205
	2	13	3	0	0	0	
	3	18	3	0	0	0	
	4	8	2	0	0	0	
	5	0	0	0	0	0	
	6	3	3	0	0	0	
	7	8	0	0	0	0	
Middle third of the adjacent tooth root	1	68	3	0	0	0	144
	2	13	2	0	0	0	
	3	35	3	0	3	0	
	4	8	0	0	0	0	
	5	0	0	0	0	0	
	6	3	5	0	0	0	
	7	1	0	0	0	0	
Apical third of the adjacent tooth root	1	18	0	0	1	0	43
	2	2	0	0	0	0	
	3	5	2	0	1	0	
	4	5	1	0	4	1	
	5	0	0	0	0	0	
	6	2	1	0	0	0	
	7	0	0	0	0	0	
Above apices of the adjacent teeth roots	1	3	0	0	3	0	28
	2	0	0	0	0	0	
	3	3	0	1	8	0	
	4	2	1	0	1	0	
	5	0	0	0	5	0	
	6	0	1	0	0	0	
	7	0	0	0	0	0	
Total		350	42	1	26	1	420

Table 2 Occurrence of ankylotic and resorptive processes

Pathological change	Impacted canines in males	Impacted canines in females	Total number of impacted canines
No pathology	123	225	348 (82.9%)
Root ankylosis (RA)	11	29	40 (9.5%)
AGRR	2	9	11 (2.6%)
PEIR	0	3	3 (0.7%)
Replacement root resorption (RRR)	2	1	3 (0.7%)
ICRR	5	3	8 (1.9%)
Co-occurrence of RA + PEIR	0	1	1 (0.2%)
Co-occurrence of RA + AGRR	0	2	2 (0.5%)
Co-occurrence of RA + ICRR	1	3	4 (1.0%)
Total	144	279	420 (100%)

26) of the impacted canines located above the root apices of adjacent teeth had a horizontal position. Also, canines with unfavorable inclination distally and palatally were located high in the maxilla, i.e., at the level of the apical third or above the root apices of the adjacent permanent teeth (Table 1). Additionally, complete transposition of the impacted canine and lateral incisor was observed in 3 impacted canines (0.71%), while 16 (3.8%) had complete transposition of the canine and first premolar.

Analysis of the occurrence of ankylotic and resorptive processes

As part of the diagnosis and treatment of impacted canines, CBCT examinations were used. The presence of ankylotic and resorptive processes evaluated by CBCT was subsequently confirmed by surgery (Table 2). During this examination, we found ankylotic changes in 56 (13.3%) impacted canines. Furthermore, we performed

CBCT examinations on patients who had previously undergone unsuccessful orthodontic traction. In these cases, we identified ankylotic changes in 5 (1.2%) canines. Given the high number of canines affected by ankylotic changes in our cohort, we decided to examine different types of these processes. In this study, RA was defined as a condition in which a periodontal space was invisible on axial CBCT scans and other multiplanar (MPR) views and/or an area of increased bone density adjacent directly to the root of the tooth, and the presence of ankylosis was also confirmed by a surgeon. Root ankylosis of this type was observed in 40 (9.5%) of the impacted canines, in 27 females and 11 males (in 2 females the canine involvement was bilateral). We determined that AGRR was present when the impacted canine on CBCT scans showed one or more of the following features: an invisible follicular sac around the crown of the canine, bone tightly adjacent to the enamel, or a dimpled enamel surface (Fig. 1). AGRR was found in 11 (2.6%) canines, with 8 females and 2 males affected and one female having bilateral involvement (patients´ ages: 34.66; 35.0; 35.41; 35.75; 38.33; 42.16; 42.33; 42.58; 42.66; 54.83). The typical diagnostic features of PEIR are the presence of resorption of the dentin of the impacted canine crown and the presence of a pit in the enamel connecting the follicular sac and the resorbed part of the crown (Fig. 3). PEIR was observed in 3 (0.7%) canines, in 2 females aged 33.25 and 37 years. Simultaneous pathology of the crown and root of the impacted canine, RA and AGRR, was found in 2 (0.5%) canines, in 2 women aged 34.75 and 53.41, and RA and PEIR in 1 (0.2%) canine, in 1 woman aged 38.41. RRR was found in 3 (0.7%) impacted canines. One case was observed in a canine after autotransplantation (male, age 13.91). The remaining two cases (female, age 13.66; male, age 16.33) were replacement root resorption without apparent cause (idiopathic RRR) (Fig. 4). ICRR was diagnosed based on the finding of a typical radiolucent lesion in the cervical part of the impacted canine root of varying extents (Fig. 2). ICRR was observed in 8 (1.9%) canines, in 2 females and 4 males (one female and one male had both canines affected). In 4 (1.0%) canines, root ankylosis was also detected in addition to ICRR.

We used generalized linear models (GLM) to analyze the occurrence of ankylosis (presence or absence) assuming binomial error distribution and logits as a link function. By fitting single-factor GLMs, we found that three predictor variables were able to improve the fit of the model and reduce AICc in comparison to an intercept-only GLM. These variables were age (ΔAICc = 203.7), position of the crown (ΔAICc = 190.9), and position of the crown tip (ΔAICc = 10.97). The other predictor variables (sex: ΔAICc = -0.08; inclination: ΔAICc = −3.79; transposition: ΔAICc = 1.63) were not supported by the data. However, when we created a set of candidate models combining more predictors, models containing age performed the best (Table 3). There are two best models whose ΔAICc are within a range of 2 from that with the lowest AICc. The first model contains the age and position of the crown tip, while the other one contains only the age. The patient's age is the variable that affects the presence of ankylosis in the canine ($p < 0.001$). The probability of developing ankylosis, therefore, increases with the patient´s age, especially after the age of 20 (Fig. 5). The probability of ankylosis in patients aged 15 years is 1.2%, whereas it is 4.3% in 20-year-olds, 14.1% in 25-year-olds, and 96.8% in 45-year-olds (Table 4). The model containing age and the position of the crown tip predicts a 50% chance of ankylosis occurring at 34.07, 30.36, 27.75, and 30.91 years of age for the cervical third level, middle third level, apical third level, and above the apices level, respectively (Fig. 6). The position of the crown tip requires further research to confirm.

Fifty-six canines affected by ankylosis were analyzed by the chi-squared test. We found that the canines of

Table 3 Statistical performance of combined model structures that achieved the lowest AICc. The differences in AICc of the two model structures are within the range of 2, indicating the highest support from data, the age of patients being in both

Model structure	AICc	ΔAICc
Age + Position of crown tip	135.15	0
Age	135.34	0.19
Age * Position of crown tip	138.74	3.59
Age + Inclination	138.85	3.70
Age + Position of crown	139.30	4.15

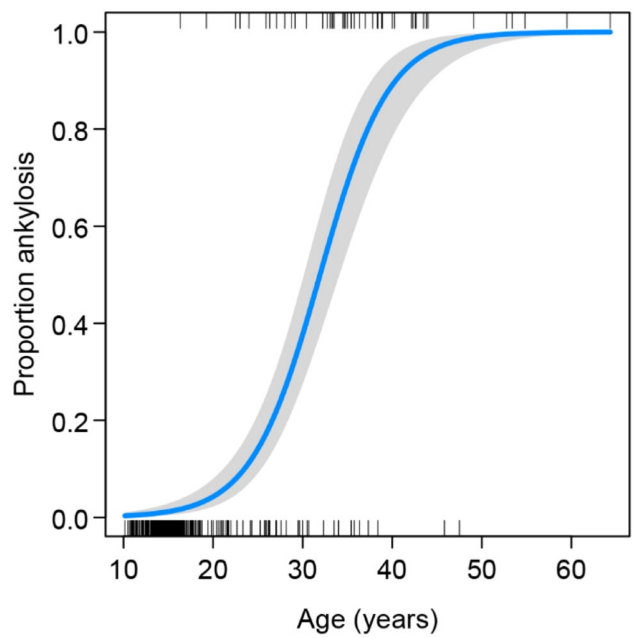

Fig. 5 The probability of the ankylosis occurrence depending on the age of the patient

Table 4 The probability of the ankylosis occurrence in the individual age groups (by 5 years)

Age (years)	Model0.logit	Probability
10	-5.70981	0.00330236
15	-4.40836	0.012028678
20	-3.10691	0.042823122
25	-1.80546	0.141187722
30	-0.50401	0.376598768
35	0.79744	0.689426606
40	2.09889	0.890795246
45	3.40034	0.967715159
50	4.70179	0.991002676
55	6.00324	0.997535355
60	7.30469	0.999328074
65	8.60614	0.999817055

females were significantly more represented than those of males (41 to 15, χ^2=12.07, df=1, p<0.001), unilateral impaction was more represented than bilateral (44 to 12, χ^2=18.29, df=1, p<0.001), the central and palatal positions of the crown relative to dental arch were more represented than the buccal and labiopalatal positions (0 to 11 to 45 to 0, χ^2=97.29, df=3, p<0.001), the positions of a crown tip at the level of the cervical third of the adjacent tooth and the middle third were more represented than the other ones (20 to 28 to 6 to 2, χ^2=31.43, df=3, p<0.001), and the mesial inclination was by far more represented than the other ones (45 to 5 to 0 to 3 to 1, χ^2=141.37, df=4, p<0.001). The frequencies for the side of impaction were found to be equal (27 to 29, χ^2=0.07, df=1, p=0.75, MSS=6145). With the sample of 63 canines, the result remained consistent (sex: 16 to 47, χ^2=15.25, df=1, p<0.001; impaction: 50 to 13, χ^2=21.73, df=1, p<0.001; position of crown: 1 to 15 to 47 to 0, χ^2=91.60, df=3, p<0.001; position of crown tip: 23 to 28 to 7 to 5, χ^2=25.06, df=3, p<0.001; inclination: 50 to 7 to 0 to 5 to 1, χ^2=131.37, df=4, p<0.001). Again, frequencies for the right and left impaction sides did not differ from each other (30 to 33, χ^2=0.14, df=1, p=0.71. MSS=3453).

Analysis of treatment methods in the evaluated cohort

A summary of the treatment methods used is shown in Table 5. In the entire cohort of 420 impacted canines, seven patients with 9 (2.1%) impacted canines did not continue with treatment. In 17 patients with 18 (4.3%)

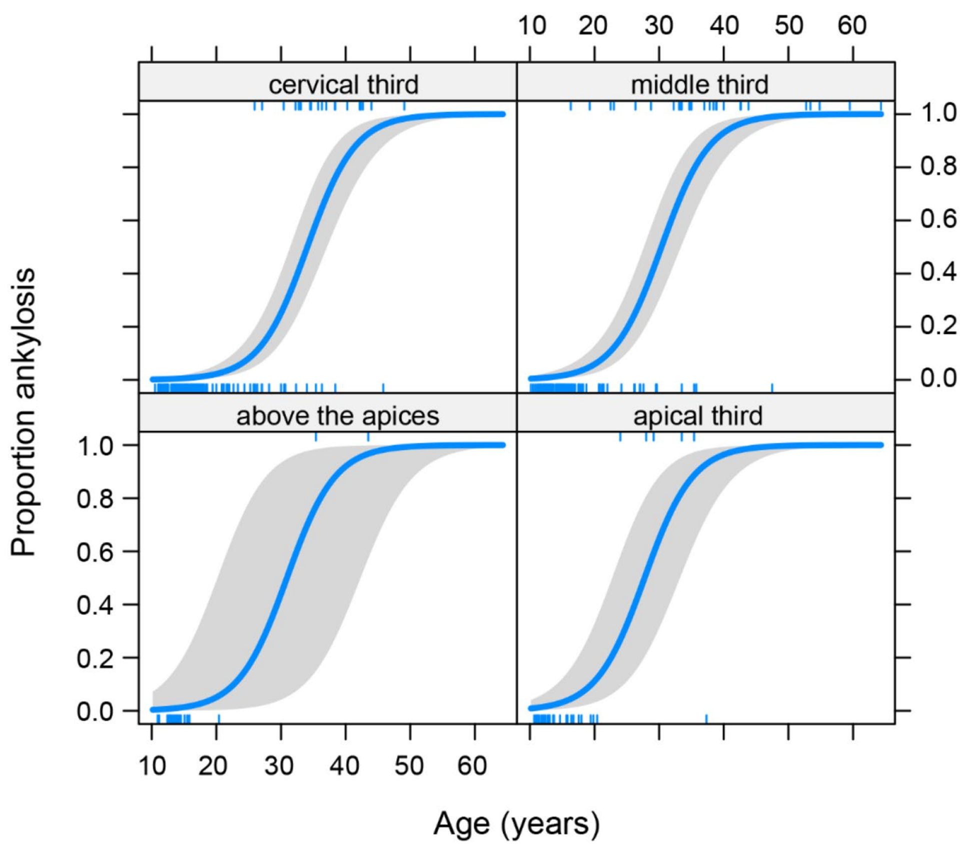

Fig. 6 The effect of the age of the patient on the occurrence of canine ankylosis at different vertical positions of the impacted canine crown tip to the adjacent tooth root as predicted by the best generalized linear model containing the age of the patient and vertical position of the crown tip. The positions include the cervical third level, middle third level, apical third level, and above the apices level. The proportion of 0.5 is achieved at an earlier age for the apical third level compared to the cervical third level, indicating varying temporal patterns for the occurrence of canine ankylosis

Table 5 Overview of the treatment methods for the impacted canines by sex and age of patients

Treatment methods	Impacted canines in males		Impacted canines in females		Total number of the impacted canines
	Age up to 20 years	Age over 20.01 years	Age up to 20 years	Age over 20.01 years	
Orthodontic alignment after surgical exposure without extractions of other permanent teeth	67 (16.0%)	11 (2.6%)	133 (31.6%)	29 (6.9%)	240 (57.1%)
Orthodontic alignment after surgical exposure with extractions of other permanent teeth	11 (2.6%)	0	20 (4.8%)	2 (0.5%)	33 (7.9%)
Surgical extraction	19 (4.5%)	9 (2.1%)	18 (4.3%)	35 (8.3%)	81 (19.2%)
Surgical extraction after failure of orthodontic traction	5 (1.2%)	5 (1.2%)	12 (2.8%)	12 (2.8%)	34 (8.0%)
Autotransplantation	3 (0.7%)	0	2 (0.5%)	0	5 (1.2%)
Spontaneous eruption after preventive procedures	11 (2.6%)	0	7 (1.7%)	0	18 (4.3%)
Refusal of treatment by the patient	0	1 (0.25%)	0	8 (1.9%)	9 (2.1%)
Total number of the impacted canines	116 (27.6%)	26 (6.2%)	192 (45.7%)	86 (20.5%)	420 (100%)

impacted canines aged 10.83 to 15.0 years, we achieved spontaneous eruption into the oral cavity after preventive procedures such as extraction of temporary teeth and/or opening of the space in the dental arch. Autotransplantation was performed in 5 patients, including 3 males aged 13.91, 14.00, 14.25, and 2 females aged 12.66 and 14.5 years. Transplantation was indicated in cases where impacted canines were positioned horizontally over the apices of adjacent teeth and crowns were buccally accessible. In one case (male, age 13.91), RRR occurred during healing. Two cases (male, age 14.25 and female, age 14.5) developed ICRR, followed by root ankylosis. A total of 273 (65.0%) impacted canines were aligned in the dental arch by orthodontic treatment after surgical exposure. Orthodontic treatment without extraction of permanent teeth was performed in 240 (57.1%) canines. In 33 (7.9%) cases of canine treatment, selected permanent teeth were extracted based on orthodontic indications. In the group of patients under 20 years, 231 (55.0%) impacted canines were aligned orthodontically, while in the group of patients over 20.01 years, only 42 (10.0%) canines were aligned. In the patients included in our retrospective study, 293 (69.7%) impacted canines were successfully brought into the dental arch after treatment. However, the three impacted canines healed with ankylosis or ICRR after autotransplantation were not considered a successful treatment outcome, as the criteria for successful autotransplant healing were not met.

Surgical extraction was performed on 115 (27.2%) impacted canines. After discussing treatment options with the patients (and his/her parents in the case of patients under 18 years of age), extraction was selected for 81 (19.2%) impacted canines. Twenty-seven (6.4%) impacted canines were indicated for extraction due to orthodontic reasons such as complete loss of space in the dental arch and/or inconvenient position for orthodontic alignment. Among these, 23 cases involved patients under 20 years of age. In 3 (0.7%) canines, the reason for extraction was the presence of a pathological finding (including 2 large follicular cysts and 1 epulis gigantocellularis) in addition to the unfavorable position. In 16 (3.8%) impacted canines, extraction was chosen as a treatment option by the patients themselves. For ankylotic and ICRR reasons, 35 (8.3%) impacted canines were indicated for extraction, in 34 cases, patients were older than 20.01 years (Table 6). Surgical extractions were also performed in 34 (8.0%) impacted canines where orthodontic treatment with surgical exposure had been initiated but had failed. Half of these cases were patients under the age of 20 years and the other half were older. Among the younger age group, the most common cause of orthodontic treatment failure was the presence of ICRR (7 canines), followed by unfavorable canine position (labiopalatal position, 4 canines), and root ankylosis

Table 6 Indications for surgical extractions of the impacted canines with respect to age and sex of patients

Indications for surgical extraction	Impacted canines in males		Impacted canines in females		Total number of the impacted canines	
	Age up to 20 years	Age over 20.01 years	Age up to 20 years	Age over 20.01 years		
Orthodontic reasons:	6	0	7	4	17	27
Loss of space in the dental arch	4	0	3	0	7	(33.3%)
Loss of space and inconvenient position	2	0	1	0	3	
Inconvenient position for orthodontic traction						
Ankylotic and resorptive processes	1	8	0	26	35 (43.2%)	
Pathological finding	0	0	1 (large follicular cyst) 1 (epulis)	1 (large cyst)	3 (3.7%)	
Patient's own choice	6	1	5	4	16 (19.8%)	
Total number of the impacted canines	19 (23.5%)	9 (11.1%)	18 (22.2%)	35 (43.2%)	81 (100%)	

Table 7 Treatment methods for impacted canines in position above the apices of adjacent teeth according to the position of the impacted canine crown in relation to the dental arch and the inclination of its longitudinal axis (column treatment method: 1 - orthodontic alignment after surgical exposure without extractions of other permanent teeth, 3a – surgical extraction due to ankylosis, 3b – surgical extraction for orthodontic reasons (complete loss of space in the dental arch and/or unfavorable position for orthodontic alignment), 3c - surgical extraction chosen by the patient, 3d - surgical extraction due to a serious complication, 4a - surgical extraction after unsuccessful orthodontic alignment due to ankylosis, 4b - surgical extraction after failure of orthodontic traction due to ICRR, 5 - autotransplantation, 6 - spontaneous canine eruption after preventive procedures, i.e. extraction of primary canine and/or orthodontic opening of the site)

Position of the impacted canine crown in relation to the dental arch	Treatment method	Inclination of the longitudinal axis of the impacted canine				Total number of the impacted canines in position above the apices of adjacent teeth
		Mesial inclination	Vertical inclination	Distal inclination	Horizontal inclination	
Palatal (PIC)	1	2	0	0	0	3
	3b	0	0	0	1	
Central (CIC)	1	1	0	0	1	20
	3a	1	0	0	0	
	3b	0	0	0	6	
	3c	2	0	0	0	
	4a	0	1	0	1	
	4b	2	0	0	0	
	5	0	0	0	5	
Buccal (BIC)	1	0	0	0	2	5
	3b	0	0	0	1	
	3d	0	0	1	0	
	6	0	1	0	0	
Total number of the impacted canines in position above the apices of adjacent teeth		8	2	1	17	28

(2 canines). In 3 canines in a significantly dislocated position, the anchorage was lost during orthodontic traction, causing a loss of space in the dental arch. In patients older than 20.01 years, the most common cause of orthodontic traction failure was the presence of some form of ankylotic or resorptive change, which occurred in 15 canines. In 2 cases, the failure was due to an unfavorable position. Impacted canines with diagnosed ankylosis or resorptive process were extracted, except for patients who refused treatment and patients where this pathology occurred after autotransplantation. We observed significant crown resorption in teeth with PEIR. Due to the risk of crown breakage after applying orthodontic traction, extraction of the affected teeth was indicated. Surgical extraction of the impacted canine as a treatment method occurred statistically significantly more often in patients older than 20.01 years ($P<0.0001$, Fisher exact test).

In 26 patients (12 females and 14 males), we observed 28 canines (2 patients had bilateral occurrence) in the position above the root apices of the adjacent permanent teeth, or the least favorable position in the vertical plane. Table 7 shows the treatment methods used for canines in this position. Three patients had 3 (0.71%) canines in complete transposition with adjacent lateral incisor, two canines were orthodontically aligned in the dental arch, and one was extracted due to crowding or lack of space in the dental arch. In 5 males and 7 females, we diagnosed 16 (3.8%) impacted canines in the complete transposition with the first premolar. Table 8 lists the treatment methods used for these canines.

Table 8 Treatment methods for impacted canines in complete transposition with the first premolar according to the position of the crown of the impacted canine in relation to the dental arch and the inclination of its longitudinal axis (column treatment method: 1 - orthodontic alignment after surgical exposure without extractions of other permanent teeth, 2 - orthodontic alignment after surgical exposure with extractions of other permanent teeth, 3 - surgical extraction, 6 - spontaneous canine eruption after preventive procedures, i.e. extraction of primary canine and/or orthodontic opening of the site)

Position of the impacted canine crown in relation to the dental arch	Treatment method	Inclination of the longitudinal axis of the impacted canine				Total number of the impacted canines in complete transposition with the first premolar
		Mesial inclination	Vertical inclination	Distal inclination	Horizontal inclination	
Palatal (PIC)	1	1	0	0	0	1
Central (CIC)	1	0	1	0	0	4
	3	0	0	0	1	
	6	0	2	0	0	
Buccal (BIC)	1	1	5	0	0	11
	2	0	1	0	0	
	3	0	0	0	0	
	6	0	4	0	0	
Total number of the impacted canines in complete transposition with the first premolar		2	13	0	1	16

Discussion

In this study, we examined 351 patients with 420 impacted upper canines. We compared our findings with a study by Lövgren et al. [37], which examined 601 patients with 724 impacted canines. Both studies had a similar sex distribution of the population, with impacted canines occurring almost twice as often in women. Unilateral impaction was four times more common than bilateral impaction. The two studies had similar prevalence rates of palatal position of impacted canines (63.6% vs. 61.0%). However, our study observed a different prevalence of central and buccal positions of canines (24.7% and 10.0%), compared to Lövgren et al.´s study (12.0% and 27.0%). We believe that the differences in prevalence are due to the assessment methods applied. We used CBCT scans, while Lövgren et al. used radiographs and surgeon´s recorded notes to assess the position of the impacted canines. The two studies also differ in the representation of surgical extraction as a treatment method. Lövgren et al. reported extraction in 144 (20.0%) of the impacted canines. In our patient cohort, 115 (27.2%) impacted canines were extracted, this can be attributed to the different age structures of the two cohorts. The age of the patients in our cohort was 10–64, while in the cohort of Lövgren et al., it was 21–23 years.

One of the objectives of our retrospective study was to analyze the methods used for the treatment of impacted canines. We start with preventive care in younger patients based on the diagnosis of the position of the maxillary permanent canine on orthopantomogram (OPG). These patients were not included in this study, because we did not aim to evaluate the effect of preventive treatment on the change in canine position. Therefore, only 18 (4.3%) canines that erupted into the oral cavity without the need for surgical exposure, were examined.

The ideal outcome of treatment of impacted maxillary canines is their presence in the dental arch so that they can perform their aesthetic and functional roles. The most common method is orthodontic alignment of the canine into the dental arch after surgical exposure. This procedure was performed in 273 (65.0%) impacted canines. In patients younger than 20 years, 75% of canines were aligned orthodontically, whereas in patients older than 20.01 years, only 37.5% were repositioned. In contrast, surgical extraction was performed in 115 (27.2%) impacted canines. While 54 (17.5%) canines were extracted in patients under 20 years of age, the number of extractions was statistically significantly higher in patients older than 20.01 years, with 61 canines (54.5%) being extracted.

The orthodontic alignment of the impacted canine requires adequate space in the dental arch. In cases when space is insufficient, the orthodontist must determine whether non-extraction or extraction procedures are necessary to create the required space. It is also important to assess whether the position of the canine is suitable for orthodontic traction. Grisar et al. [38] reported that critically impacted canines (those associated with local pathology, e.g. presence of odontoma, ankylosis, root dilaceration, in transposition, with the horizontal, high, or inverted position) are at a higher risk of failure with conventional orthodontic and/or surgical treatment. However, there are only a few relevant studies that explore the treatment of such impacted canines and most of the published papers are case reports. In this study, we analyzed the use of various treatment methods for critically impacted canines. In the subgroup of 28 canines that were in a high position above the root apices of the adjacent permanent teeth, surgical extraction was the predominant treatment method accounting for 16 canines (57.1%). Six (21.4%) canines were orthodontically aligned into dental arch, one (3.6%) canine erupted spontaneously after preventive procedures, and autotransplantation was carried out in 5 canines (17.9%). Canine extractions were mostly performed when the crown was located in the center of the alveolar bone. We view this position as critical for performing surgical exposure without traumatizing the CEJ area of the canine and subsequent orthodontic traction. Surgical extraction was also a prevailing treatment in the subgroup of 26 canines with horizontal longitudinal axis inclination. It was performed in 17 canines (65.4%), while 5 canines (19.2%) were autotransplanted and four (15.4%) were orthodontically aligned. According to Liu et al. [5], horizontally positioned canines are more difficult to treat conventionally but occur less frequently. In our study, horizontally positioned canines were observed in 26 (6.2%) canines. Complete maxillary canine-lateral incisor transposition was found in 3 (0.71%) canines, two were orthodontically treated, and one required extraction. As such, we are not clear whether to consider this type of transposition as a critically impacted tooth. In our study, complete maxillary canine-first premolar (Mx.C.P1) transposition occurred in 16 (3.8%) canines, which is a higher incidence than in other studies (0.135–0.510%) that focused on impacted canines [39, 40]. One canine (6.25%) was extracted due to the combination of transposition, high horizontal position above the premolar apexes, and deep location of the canine crown in the center of the alveolar bone. In 6 (37.5%) canines, the spontaneous eruption was achieved after opening the space in the dental arch, and nine (56.25%) were aligned orthodontically after surgical exposure. In all cases, we accepted the transposed position of the canine and first premolar. In only one patient, we aligned a canine after the extraction of the first premolar whose root was resorbed. According to our experience, we do not consider complete Mx.C.P1transposition as a critically impacted tooth if the inclination of the longitudinal axis is vertical or mesial and if the transposed order of the teeth is kept. This procedure and its long-term results are well documented in the literature [41–44]. Some authors recommend correcting the transposed position by orthodontic treatment and alignment of the canine into the proper position within the dental arch. This procedure is lengthier and requires performing more complex torquing movements with the canine and first premolar roots, which may cause tissue damage [20, 45–49]. If the goal of treatment is to place impacted Mx.C.P1s into the arch with correction of the transposition, these canines should be considered critically impacted. Chaushu et al. [32] describe the L-PIC as a separate, but rarely occurring entity that is associated with some degree of transposition of the canine and lateral incisor. This is consistent with our findings. We observed labiopalatal position in 7 (1.7%) impacted canines. For the correct diagnosis of L-PIC, CBCT examination is essential. Chaushu et al. and Becker [20, 32] recommend performing surgical exposure of the impacted canine crown from the labial side and directing orthodontic traction distolabially first. As soon as the crown of the canine is displaced from the palatal side of the central incisor, traction can be redirected distally. For this movement of the canine, it is necessary to leave sufficient space between the roots of the central and lateral incisor, the so-called window of opportunity. Based on our experience, the aforementioned canine movement is challenging for the anchorage of the distal teeth. When treating impacted canines, we used the Burstone-type steel transpalatal arch and the segmental technique to enhance the anchorage value of the orthodontic appliance. Loss of anchorage due to orthodontic traction was recorded in three L-PIC patients. This led to a change in the initial treatment plan and the extraction of the impacted canine. In three patients, L-PICs were orthodontically aligned in the dental arch, whereas in two patients, the adjacent lateral incisors were extracted due to significant malformation of the crown and root shape or due to significant root resorption caused by canine pressure. One patient chose L-PIC extraction without orthodontic treatment. We consider L-PIC to be critically impacted and recommend enhanced anchorage of mini-screws and mini-plates when planning orthodontic mechano-therapy.

We indicate autotransplantation in canines that are horizontally placed above the root apices of adjacent teeth and whose crowns are buccally accessible. This position of the impacted canine should be considered critical for orthodontic traction, with a high risk of failure and alternative treatments such as autotransplantation or surgical extraction may be necessary. There is currently enough scientific information available regarding healing transplanted teeth [50–54]. In order to minimize the risk of failure, we used 3D replicas, which helped to reduce the extra-oral time of the donor tooth [55–57]. To avoid replacement root resorption during the healing process, the transplanted tooth should be placed in the recipient socket in a way that does not put pressure on it from the tongue, cheeks, or occlusion. It should also be held in place with a flexible fixation or splint that allows functional movement without interfering with the healing of the PDL [58, 59]. When autotransplanting a tooth with finished root development, endodontic treatment should be conducted between 2 and 4 weeks after transplantation. At this stage, the tooth is still mobile, so only a simplified root canal preparation and filling with calcium hydroxide should be done. The definitive endodontic treatment can be performed approximately 4 months after transplantation [27, 60, 61]. Antibiotic coverage improves results in autotransplanted teeth. While the treatment protocols and success rate of premolar autotransplantation are well documented and described in long-term studies, there is less data on autotransplantation of impacted canines in the literature, which suggests that it is a less frequently indicated treatment method. Long-term complications associated with this method include ICRR and RRR [62, 63]. The prognosis of autotransplanted teeth depends on many other factors such as the age of the patient, the stage of root development and position of the transplanted tooth, atraumatic surgical design procedure, and endodontic treatment in teeth with complete root development. In our experience, the dimensions of the alveolar bone or the possible lack of bone at the recipient site can also play an important role in healing the autotransplanted impacted canines. In this study, autotransplantation was performed in only 5 (1.2%) canines. The healing of the autotransplanted canine resulted in RRR in one case and ICRR in two cases, followed by root ankylosis. In these 3 (0.75%) canines, we do not consider the outcome to be successful due to the occurrence of ICRR and/or RRR. One patient lost his canine 13 years after autotransplantation, the other two patients still have their canines in place. Grisar et al. [64], in their systematic review and meta-analysis focusing on the autotransplantation of impacted canines concluded that there is insufficient scientific evidence to specify the indications and contraindications for canine autotransplantation. The analysis also showed that there is no clear consensus on what outcome of autotransplanted canines should be considered successful. Some authors believe that the mere presence of a tooth in the oral cavity is a successful outcome. From this perspective, ankylosis and replacement root resorption after transplantation should not be viewed as a failure. If the tooth is lost and the root is replaced by bone formed by the process of replacement resorption, sufficient bone is formed for intraosseous dental implant insertion [65]. According to more rigorous authors and also in our opinion, only a completely healed autotransplant without complications (i.e., no inflammatory resorption, no ankylosis, no pocketing) can be considered a successful outcome.

Before starting orthodontic treatment of impacted canines, it is also necessary to rule out the presence of pathological changes, especially various forms of ankylotic and resorptive processes. Premolars should not be extracted unless it is clear whether or not the impacted canine is ankylotic [66, 67]. Diagnosing impacted canine ankylosis can be challenging. In a study conducted by Ducommum et al. [68], the incidence of ankylosis was compared using panoramic images, CBCT scans, and histologic sections of extracted permanent molars. The researchers concluded that CBCT is a useful method for diagnosing ankylosis. However, they found that false-positive results could occur on CBCT images. Therefore, they recommended using clinical findings and anamnestic data for a definitive diagnosis of ankylosis. Ankylosis on CBCT scans was also investigated by Rege et al. [69], who assessed ankylosis with the technique of quantification of mean pixel intensity and variation of pixel intensity. As the normal width of the PDL ranges from 0.15 to 0.38 mm, they recommend CBCT images with a voxel size of 0.2–0.25 mm for the evaluation of this condition. Their study did not find any significant association between ankylosis and age. However, the authors noted that the assessment of ankylosis on CBCT can be challenging due to the difficulty in assessing teeth in the required planes. This makes the assessment of PDL and ankylosis areas complicated and can lead to incorrect diagnoses. To improve the diagnosis of ankylosis on CBCT scans, considerable efforts have been made such as using special software [70], setting a CBCT protocol [71], or the assessment methodology [72, 73].

Considering the above, we diagnosed ankylosis according to the typical CBCT findings and confirmed it during a surgical procedure (extraction or exposure). Koutzoglou et al. [74] discovered that the incidence of ankylosis was independent of sex and canine position but was dependent on age, surgical technique employed (higher incidence in the close exposure technique), and severity of impaction evaluated on orthopantomograms. It is important to note that the authors used a broad definition of ankylosis in their studies, which included immobile impacted canines, all types of external tooth resorption, and other factors. In our study, comprehensive diagnosis using CBCT and confirmed by clinical findings during surgery allowed us to differentiate between ankylotic (RA, AGRR, PEIR, RRR, and their combinations) and resorptive (ICRR) changes. For ankylotic changes, we did not demonstrate a statistically significant dependence on patient sex or canine position and inclination. However, ankylosis occurrence was significantly dependent on increasing patient age. The probability of ankylosis in patients aged 15 years is 1.2%, whereas it is 4.3% in 20-year-olds, 14.1% in 25-year-olds, and 96.8% in 45-year-olds. Our findings are consistent with the results of Becker and Shaushu [75], who reported that the prognosis for successful orthodontic alignment of impacted canines in adults worsens with age. The dependence of the success of forced eruption of impacted teeth on age was also demonstrated by Kim et a. [76]. In our patient cohort, we observed ankylosis in only 4 (1%) impacted canines in patients who started treatment before the age of 20 years. Based on typical CBCT findings, we diagnosed idiopathic RRR in 2 canines. One canine experienced RRR after autotransplantation and another one RA in the context of orthodontic traction failure after surgical re-exposure, with the first exposure being performed as a closed technique. Cassina et al. [77] point out that closed surgical exposure poses a higher risk of ankylosis and subsequent traction failure than open exposure.

For a tooth to move, it must have an intact PDL [20]. In all types of ankylotic and resorptive changes, the PDL is altered and the affected tooth does not erupt or respond to the applied orthodontic force by moving. To allow orthodontic movement of an impacted canine with root ankylosis, it is recommended to break the ankylotic bone bridges by performing gentle luxation movements [6, 13–15]. Based on our experience, we concur with other authors that the success rate of this method is limited [78]. According to Garcia [18] the risk of damage to the PDL in the cervical region must be considered when performing a surgical coronal release, especially in deeply placed teeth. To minimize the risk of re-ankylosis, orthodontic traction should be applied immediately after the surgical procedure because the motion generated promotes the diffusion of desmodontal fibroblasts to the surface of the root lesion and protects it against the formation of an ankylotic junction. The presence of apical ankylosis after failed orthodontic traction is explained by the momentary interruption of traction. During orthodontic movement of the impacted tooth, the apex may come into close contact with densely mineralized nonresorbable bone. As a result of the pressure, ischemia and necrosis of the PDL occur. This situation does not pose a risk if the orthodontic traction continues. However, if the movement is interrupted, direct bone-root contact leads to the formation of an ankylotic bridge.

Both in clinical practice and professional literature, it has been observed that in some cases, an impacted tooth initially responds well to orthodontic traction but then suddenly stops moving. If the impacted canine does not move after the orthodontic force is applied, this condition must be diagnosed as soon as possible and the treatment strategy should be changed. Failure to do so can result in unwanted movement of the anchor teeth due to reciprocal forces. At the same time, apical root resorption of adjacent teeth and significant prolongation of treatment may occur [78, 79]. The possible reason for this may be due to trauma caused to the PDL during surgical exposure or excessive force being applied to the tooth [20, 66]. According to Becker [21], when performing open surgical exposure, particularly on teeth that are deeply seated, the surgeon may need to perform a larger exposure to keep the wound open for attachment bonding. This procedure can potentially lead to mechanical damage to the CEJ area and subsequently to the development of ICRR. The risk of ICRR is also increased by the penetration of orthophosphoric acid into the CEJ area. Orthodontic traction can potentially damage or cause necrosis of the cells in the cervical region, especially when tipping movements are involved. If the tooth being treated is unresponsive to the forces initially applied, some orthodontists may apply more force. However, heavy forces should be avoided as they can cause apical root resorption of the anchor teeth. In our study, ICRR was diagnosed in 8 (1.9%, 7 canines under 20 years, 1 over 20.01 years), and ICRR concomitant with RA in 4 canines (1%, 2 canines under 20 years, 2 canines over 20.01 years). After thoroughly examining clinical data, we found an association between ICRR in canines and surgical procedures such as deep-seated canine surgical exposure, surgical re-exposure, and autotransplantation. In the cases of ICRR, surgical luxation, and immediate orthodontic traction are not effective, unlike in cases of ankylosis. The treatment for ICRR depends on the extent of tooth involvement. In incipient cases of ICRR, exposure of resorption lacunae with the removal of dentinoclastic material and granulation of soft tissue is performed. The defect must be filled with restorative materials. The tooth can be orthodontically extruded into position so that the healthy dentin margin forms a gingival sulcus. In advanced stages of ICRR of impacted canines, extraction is indicated. We applied the above-described treatment (exposure, removal of dentinoclastic and granulation soft tissue, application of glass-ionomer cement and Emdogain) in one canine with ICRR four years after autotransplantation but we did not achieve a complete cessation of the ICRR process. ICRR continued at a slow rate, gingival recession developed, and 13 years after autotransplantation, the canine crown broke away from the tooth root, and the root had to be extracted. The impacted canines diagnosed with ICRR as the cause of failure of orthodontic traction were surgically extracted.

The strength of this research is that this study included patients with impacted canines who were diagnosed and treated by a single orthodontist, with surgical procedures performed by one surgeon over the 20-year follow-up period. The retrospective nature of our study allowed us to accurately diagnose ankylotic and resorptive changes of impacted canines based on CBCT, which was subsequently confirmed by the surgeon. One of the next benefits of our study is the age composition of the cohort, as 112 (26.7%) of the impacted canines were observed in patients older than 20.01 years. Therefore, we found a high number (61 and 14.5%) of canines with ankylotic and resorptive changes. To our knowledge, no study of this size with a similar age structure of the included patients has been published before.

Finally, our results suggest that ankylotic changes are more typical for older patients and are probably linked to biological processes associated with aging. In contrast, ICRR is typical for younger patients and tends to be a consequence of PDL damage. From a clinical perspective, these findings should be taken into account when planning orthodontic treatment. It is advisable to begin orthodontic treatment for impacted canines as soon as possible after diagnosis, especially in younger patients, as they are less likely to develop ankylotic changes.

Conclusions

Orthodontic alignment after surgical exposure of the impacted canines is a commonly used method with predictable results. The success rate of this treatment can be improved by carefully selecting patients and choosing the appropriate surgical technique based on CBCT examination. The findings of the presented retrospective study of 351 consecutive patients with 420 impacted maxillary canines suggest the following conclusions:

- Two hundred and seventy-three (65.0%) impacted canines were aligned in the dental arch by orthodontic treatment. This treatment method was most frequently employed in patients under 20 years of age (75% of impacted canines). In patients older than 20.01 years, only 37.5% of canines were orthodontically aligned.
- Surgical extraction was performed in 115 (27.2%) impacted canines. This method of treatment was statistically significantly more common in the group of patients older than 20.01 years (54.5% of canines). In patients younger than 20 years, this method was indicated in 17.5% of canines.
- Autotransplantation was used in 5 (1.2%) canines in a horizontal position above the apices of adjacent teeth whose crowns were buccally accessible.
- Ankylotic changes were observed in 61 (14.5%) impacted canines. Root ankylosis occurred in 40 (9.5%) canines, AGRR in 11 (2.6%), PEIR in 3 (0.7%) canines, and simultaneous occurrence of the above pathologies in 3 (0.7%) canines. RRR after autotransplantation was observed in 1 (0.25%) canine and idiopathic replacement root resorption in 2 (0.5%) canines.
- The probability of developing ankylosis increases with age, especially after the 20th year of life of the patient. The probability of ankylosis is 1.2% at age 15, 4.3% at age 20, 14.1% at age 25, and 96.8% at age 45 years.
- ICRR was found in 8 (1.9%) canines. In 4 (1.0%) cases, we observed root ankylosis in addition to ICRR. The occurrence of ICRR is more typical of younger patients and is a consequence of PDL damage during surgery.
- The following teeth are recommended to be considered as critically impacted canines with a high tendency to failure of orthodontic traction: canines whose crown is in a high position above the root apices of adjacent teeth and deep in the center of the alveolar bone, canines with a horizontal inclination of the longitudinal axis, canines with a labiopalatal position and canines with ankylotic and/or resorptive changes.

Abbreviations

3D	Three-dimensional
AGRR	Age-related replacement resorption
AICc	Akaike´s information criterion
ANOVA	Analysis of variance
BIC	Buccally impacted canine
CBCT	Cone beam computed tomography
CEJ	Cementoenamel junction
CIC	Centrally impacted canine
DICOM	Digital imaging and communications in medicine
ECR	External cervical resorption
GLM	Generalized linear models
HO	Null hypothesis
ICRR	Invasive cervical root resorption
IRM	Intermediate restorative material
L-PIC	Labiopalatally impacted canine
MPR	Multiplanar
MSS	Minimum sample size
MTA	Mineral trioxide aggregate
Mx.C.P1	Maxillary canine-first premolar
OPG	Orthopantomogram
PDL	Periodontal ligament
PEIR	Pre-eruptive intracoronal resorption
PIC	Palatally impacted canine
RA	Root ankylosis
RRR	Replacement root resorption
SD	Standard deviation
ΔAICc	Difference in Akaike´s information criterion

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Author contributions
Pavlina Cernochova and Cenek Cernoch contributed equally to this work.P.C. performed diagnostics and orthodontic treatment of patients and contributed to conceptualization, methodology, sample collection, data evaluation (investigation), original draft preparation, resources, writing, and editing; C.C. contributed to sample collection, data evaluation (investigation), resources, writing and editing; E.T. contributed to statistical analysis; L.I.H. contributed to statistical analysis, reviewing and editing; K.K.K. contributed to surgical treatment of patient.

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Data availability
The data that support the findings of this study are available on request from the corresponding author.

Declarations

Ethics approval and consent to participate
This study follows the principles of the Declaration of Helsinki. All patients (and a parent in patients under 18 years of age) signed an informed consent that their radiological findings (without disclosing their identities) may be used for future research into maxillary canine impaction. The Committee for Ethics of St. Anne´s University Hospital Brno, Czech Republic (Approval no. 01G/2020) approved the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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