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Computed tomographic findings in incisors and canine teeth with equine odontoclastic tooth resorption and hypercementosis: a retrospective study in 115 Warmblood horses

Natalie D. Bearth[1], Felix Theiss[1], Henning Richter[2], Jonna Gimmi[2], Paul Torgerson[3] and Stefanie Ohlerth[2]

[1] Department of Equine Surgery, Vetsuisse Faculty, University of Zurich, Zurich, Switzerland
[2] Clinic for Diagnostic Imaging, Vetsuisse Faculty, University of Zurich, Zurich, Switzerland
[3] Section of Epidemiology, Vetsuisse Faculty, University of Zurich, Zurich, Switzerland

Summary: Computed tomography (CT) has become a routine method to examine the equine skull. Its clinical use for the diagnosis of diseases of the incisors and canine teeth has not been reported so far. The goal of this study was to study the prevalence and relationship of single CT features and equine odontoclastic tooth resorption and hypercementosis (EOTRH) in equine incisors and canine teeth. In this descriptive retrospective study, helical CT studies of 115 Warmblood horses of the age of 5 years or older examined between 2007 and 2020 for reasons unrelated to the incisors and canine teeth were included. Resorption in the crown or root, hypercementosis, widening of the periodontal space, clubbing of the root, lysis of the lamina dura, an abnormal pulp cavity and fracture of the root were recorded in all incisors and canine teeth. The length of the pulp cavity and the labial and lingual/palatal length of the enamel and root was measured in each incisor and canine tooth. Additionally, the angulation was assessed in each incisor. The variable EOTRH was defined based on the presence of resorptive lesions, hypercementosis and clubbing. In result median age of the included horses was 12 years (range, 5–29 years). With regard to the investigated population of horses, 44.3% of all horses had normal incisors whereas 55.7% of the horses had mild EOTRH changes in one incisor at least. Regarding the canine teeth, 54.7% of the horses had normal canine teeth whereas 43.3% horses had mild EOTRH in one canine tooth at least. With regard to all investigated teeth, 868 teeth (53.0%) were classified as normal, whereas 769 incisors and canine teeth (47.0%) showed at least one abnormal CT criterion. Clubbing of the root and hypercementosis were most common (37.1% and 22.7%, respectively) and EOTRH was present in 27.1% of all teeth. Mild changes were more common than moderate or severe abnormalities. In the lower jaw, hypercementosis and widening of the periodontal space at the anatomical root and apex of the root was significantly more frequent ($p = 0.004$ and 0.02), whereas clubbing of the root was more common in the upper jaw ($p = 0.009$). In canine teeth, resorption in the anatomical crown and anatomical root, widening of the periodontal space, clubbing and lysis of the lamina dura were significantly more common whereas hypercementosis was more common in incisors ($p < 0.001$). Frequency of certain CT changes significantly increased from central to middle and corner incisors. Severity of all single CT criteria as well as prevalence and severity of EOTRH significantly increased with age ($r = 0.08–0.56$). Linear forward and backward multivariate regression analysis confirmed a significant association between prevalence and severity of EOTRH and age, changes of the pulp cavity, widening of the periodontal space at the anatomical rootand incisor group (central, middle, corner) ($p = 0.01 – < 0.001$). In conclusion computed tomographic changes of the incisors and canine teeth are common and age-related in Warmblood horses. Therefore, treatment of EOTRH should not be based on diagnostic imaging alone, but always in combination with a thorough clinical examination.

Keywords: EOTRH, CT, dentistry, horse, incisors, canines

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Correspondence: Natalie Desirée Bearth, Vetsuisse Faculty Zuerich, Clinic for Horses, Winterthurerstrasse 260, 8057 Zuerich; natalie.bearth@outlook.de

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Introduction

Equine odontoclastic tooth resorption and hypercementosis (EOTRH) is a common and painful disease in elderly horses (*Gregory* et al. 2006, *Baratt* 2007, *Hüls* et al. 2012). It is characterized by odontoclastic resorption of the reserve crown or the tooth root due to inflammation and reparative hypercementosis i.e. deposits of cementum at the reserve crown and root with subsequent bulbous swelling (*Staszyk* et al. 2008, *Sykora* et al. 2014, *Lorello* et al. 2016). The causes of EOTRH are multifactorial where high biomechanical stress acting on the periodontal ligament represents the initiating cause (*Rehrl* et al. 2018). The periodontal ligament provides fixation of the tooth root and reserve crown in its alveolar compartment. Collagen fibers and blood vessels of the periodontal ligament damper acting chewing forces (*Mitchell* et al. 2003, *Staszyk* und *Gasse* 2005). The age-related decrease in the teeth angle of the upper and lower arcade of the incisors increases the biomechanical forces acting on the periodontal ligament and thus promotes diseases such as EOTRH (*Habermehl* 1981, *McMullan* 1983, *Schrock* et al. 2013b). Sustained eruption of the tooth, compensating for normal tooth wear, maintains occlusion of corresponding teeth (*Staszyk* et al. 2006a). As tooth growth ceases with increasing age, continual eruption leads to shortening of the reserve crown and at a later stage of the tooth root. Accordingly, the attachment surface of the tooth decreases and the chewing forces on the remaining surface increases (*Staszyk* et al. 2006b). Using micro-CT investigations in combination with finite-element-analysis the biomechanical properties of the periodontal ligament in healthy incisors were determined (*Schrock* et al. 2013a). It was shown that incisor growth was able to fully compensate occlusal wear for a limited period of time but also disclosed reduced intra-alveolar tooth length to result in altered biomechanical forces acting on the periodontal ligament. The timing of these morphodynamic and biomechanical changes is13 to 15 years after eruption (*Schrock* et al. 2013b, 2013c). In incisors, periodontal areas with high biomechanical forces, i.e. the palatal/lingual area near the apex of the root, correspond to the location of initial resorptive lesions (*Schrock* et al. 2013b). It was postulated that high local traction forces acting on the periodontal ligament led to local overstretching of collagen fibres. Resulting micronecrosis may predispose for the development of periodontal disease and thereby favour the development of EOTRH (*Schrock* et al. 2013a, *Schrock* et al. 2013c). However, further biomechanical, cell biological and microbiological studies are required to clarify a correlation between age-related changes in the incisors and EOTRH. Besides the increased biomechanical forces, secondary bacterial colonization is assumed to be another triggering factor for EOTRH. In a study of 44 horses, Tannarella spp. and Treponema spp. were detected in the gingival cleft of all 23 animals showing signs of EOTRH. In contrast, these bacteria were found in only about 50 % of unaffected horses (*Sykora* et al. 2014). The persistent infection of the gingival cleft results in the constant recruitment of odontoclastic cells which initiate resorptions at the dental structures. Subsequently the resorbed dental substances trigger the deposition of large amounts of irregular cementum (*Sykora* et al. 2014).

EOTRH occurs mainly on incisors and canine teeth (*Staszyk* et al. 2008), less so on premolar (*Staszyk* et al. 2008) and molar teeth (*Moore* et al. 2016). The prevalence and severity of radiographic changes indicative of EOTRH increase with age (*McMullan* 1983, *Simhofer* und *Kowelka* 2012). EOTRH is typically visible at the age of 15 years and older (*Staszyk* et al. 2008, *Earley* et al. 2011, *Sykora* et al. 2014, *Schröder* et al. 2014, *Lorello* et al. 2016, *Rehrl* et al. 2018). A recent study found that all horses older than 14 years showed radiographic changes of EOTRH, and all horses older than 28 years had at least moderate radiological changes on the incisors (*Rehrl* et al. 2018, *Albers* et al. 2022). This indicates that mild changes are associated with the normal aging process (*Rehrl* et al. 2018, *Rehrl* et al. 2022). Radiographically, an increased probability of resorption and hypercementosis was observed with increasing age without significant differences between genders (*Smedley* et al. 2015, *Henry* et al. 2017, *Limone* 2020) or breeds (*Henry* et al. 2017).

Affected horses show a wide range of clinical symptoms of varying severity with abnormalities found not only in the affected incisors and canine teeth but also the periodontal space and the surrounding bone (*Hüls* et al. 2012, *Earley* und *Rawlinson* 2013). Bulbous enlargement, increased mobility, fractures of affected teeth or missing teeth may be observed. Changes of the periodontal space include periodontitis, gingivitis, gingival hyperplasia or recession, or draining tract formation associated with periapical abscessation. Moreover, alveolar bone protrusion may be present. In contrast to the incisors, cheek teeth show less periodontal changes.

Until now, the diagnosis of EOTRH-affected incisors and canines has been made based on clinical and radiographical findings. Radiographically, resorptive lesions of the tooth crown or root may be present in the cementum, enamel, dentin and occasionally in the pulp cavity (*Klugh* 2004, *Gregory* et al. 2006, *Baratt* 2007, *Kreutzer* et al. 2007, *Staszyk* et al. 2008, *Earley* und *Rawlinson* 2013, *Smedley* et al. 2015, *Lorello* et al. 2016). Root and reserve crown enlargement due to hypercementosis can be seen. As equal to resorption or hypercementosis, changes of the periodontal space and the surrounding alveolar bone were described in the literature, e.g. decreased width of periodontal ligament space, loss or disruption of the pulp cavity, intraalveolar root fractures, fractures of the crown or alveolar bone loss. Recently, a post-mortem study comparing clinical, radiographic, macroscopic and micro-CT findings in incisors with EOTRH (*Albers* et al. 2022) confirmed that the prevalence of lesions on incisors increased with age and formed first on the palatal/lingual side of the incisors. The study also stated that many clinically and radiologically healthy teeth were abnormal on macroscopic (13.7 %) and micro-CT examinations (58.1 %). The authors hypothetized that the detection of subtle changes is limited on a dorsoventral intraoral radiograph, in particular due to the typical localization of lesions on the palatal/lingual side of the incisors (*Albers* et al. 2022).

The use of conventional CT in horses with EOTRH has not been reported so far. So far, only a limited number of studies investigated the prevalence of EOTRH.

The goal of this study was therefore to investigate the prevalence and relationship of single CT features and EOTRH at the level of the individual tooth as well as the horse diagnosed with CT in equine incisors and canine teeth.

Materials and methods

Animals

All CT studies performed between January 2007 and March 2020 at the Equine Department, Zurich, were considered for the present study. From these studies, only Warmblood horses of the age of 5 years or older that underwent a CT examination of their head for reasons unrelated to the incisors or canine teeth were included. Images that were not of diagnostic quality or showed motion artifacts were excluded.

Computed tomographic examination

Horses were scanned either in general anaesthesia and in dorsal recumbency (from 2007 to May 2017), or in a standing position with sedation (June 2017 – March 2020). Transverse contiguous slices of the head were obtained in a helical mode from the incisors to the cribriform plate with a 40-slice CT scanner (Sensation Open, Siemens). Settings of 140 KV, 300 mAs, 1 s tube rotation, a pitch of 0.55, and an increment of 1.2 mm were used as well as a 3 mm slice collimation. The data were reconstructed to image series with 1.5 mm slice thickness using a medium-frequency image reconstruction algorithm (soft tissue) and a high-frequency image reconstruction algorithm (bone), respectively. Computed tomographic images were transferred to a workstation and reviewed by a board-certified radiologist (SO) and the first author (NB) with dedicated software using multiplanar and 3D-reconstruction modes (Horos 2K™ Version 2.2.0; IntelliSpace PACS Radiology, Version 4.4, Philips). A bone window was used for the assessment of bony and dental structures (window width, 3600 Hounsfield units; window level, 600 Hounsfield units).

Computed tomographic criteria and measurements

Data sheets evaluating the presence or absence of CT findings were compiled for each incisor and canine tooth in all horses. In all incisors and canine teeth, the following CT criteria were assessed and categorized (Figure 1): resorptive lesions in the crown or root (no lesion; 1–3 lesions ≤ 3 mm each; 1 lesion ≥ 3 mm or diffuse resorption), hypercementosis (no hypercementosis; hypercementosis with a rippled tooth surface and a mildly blunted apex; hypercementosis with clubbing of the root and a tapering root; hypercementosis with clubbing of the root and a cylindric root), clubbing of the root without hypercementosis (no clubbing; clubbing with a tapering tooth root; clubbing with a cylindric tooth root), pulp cavity (normal; closed; lysis and/or containing gas), widening of the periodontal space either at the apex of the root or at the anatomical root (normal

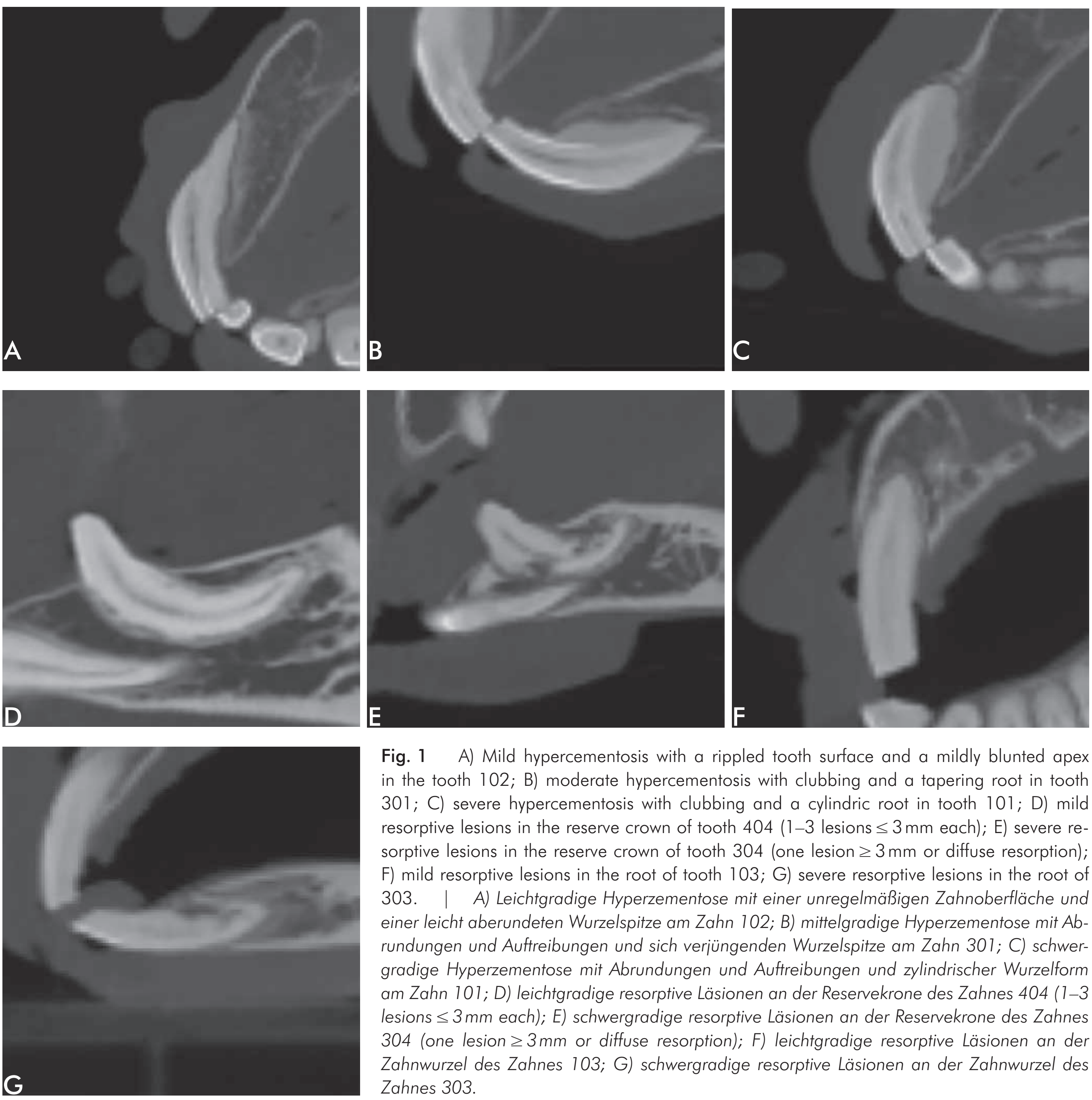

Fig. 1 A) Mild hypercementosis with a rippled tooth surface and a mildly blunted apex in the tooth 102; B) moderate hypercementosis with clubbing and a tapering root in tooth 301; C) severe hypercementosis with clubbing and a cylindric root in tooth 101; D) mild resorptive lesions in the reserve crown of tooth 404 (1–3 lesions ≤ 3 mm each); E) severe resorptive lesions in the reserve crown of tooth 304 (one lesion ≥ 3 mm or diffuse resorption); F) mild resorptive lesions in the root of tooth 103; G) severe resorptive lesions in the root of 303. | *A) Leichtgradige Hyperzementose mit einer unregelmäßigen Zahnoberfläche und einer leicht aberundeten Wurzelspitze am Zahn 102; B) mittelgradige Hyperzementose mit Abrundungen und Auftreibungen und sich verjüngenden Wurzelspitze am Zahn 301; C) schwergradige Hyperzementose mit Abrundungen und Auftreibungen und zylindrischer Wurzelform am Zahn 101; D) leichtgradige resorptive Läsionen an der Reservekrone des Zahnes 404 (1–3 lesions ≤ 3 mm each); E) schwergradige resorptive Läsionen an der Reservekrone des Zahnes 304 (one lesion ≥ 3 mm or diffuse resorption); F) leichtgradige resorptive Läsionen an der Zahnwurzel des Zahnes 103; G) schwergradige resorptive Läsionen an der Zahnwurzel des Zahnes 303.*

i.e. < 2 mm; 2–4 mm; ≥ 4 mm), decreased width of the periodontal space (no; yes), lysis of the lamina dura (no; yes), and fracture of the root (no; yes). The variable EOTRH was defined and categorized based on the variables resorption in the crown or root, hypercementosis and clubbing of the root: mild (no resorption in the crown or root; and hypercementosis with a rippled tooth surface and a mildly blunted apex), moderate (resorption in the crown or root with 1–3 lesions of a size ≤ 3 mm and/or hypercementosis with a rippled tooth surface and a mildly blunted apex), or severe (resorption in the reserve crown, crown or root 1 lesion ≥ 3 mm or diffuse resorption; and/or hypercementosis with clubbing and a cylindric root).

The following measurements were performed in each incisor on reconstructed sagittal CT images: length of the pulp cavity, labial and lingual/palatal length of the enamel and root, respectively. In canine teeth, the length of the pulp cavity was measured only.

On sagittal images, the angulation was determined for each incisor and defined as the angle between 3 reference points. The centre of the occlusal surface represented the first reference point. Then, a quadrilateral was drawn between the endpoints of the labial and lingual/palatal enamel and cementum layers. The intersection of the diagonals represented the second reference point. Finally, a vertical line was drawn from the ventrorostral endpoint of the crown of the second premolar to either the outer contour of the compact bone of the mandible (lower jaw) or to the nasoincisive notch (upper jaw). The midpoint of either distance served as the third reference point. The image plane had to be moved sagittally to connect the reference points for the measurement of the angle.

Statistical analysis

Descriptive statistics were calculated for categorized and continuous variables, either for all horses or for three different age groups (age group 1: 5–10 years; age group 2: 11–15 years; age group 3: >15 years). On the level horse, the tooth showing the most severe EOTRH changes was decisive for the overall EOTRH grade of each horse.

Due to not normally distributed data (Shapiro-Wilk test) and small cell number, nonparametric tests were applied. All statistical analyses were performed on the level tooth. The Mann-Whitney test was used for comparison of two independent samples (difference in frequencies of CT abnormalities in the upper versus the lower jaw, in incisors versus canine teeth, and between the first, second and third incisors, respectively). Associations between continuous variables (age, dental measurements) and categorized variables (single CT abnormalities, EOTRH) were analyzed with Spearman correlation coefficients. Associations between continuous variables were analyzed with Pearson correlation coefficients. Finally, a multivariate linear regression model with forward and backward stepwise procedure was calculated for EOTRH as the dependent variable and all significant variables from the former correlation analyses as predictors. Because of repeated measures for each horse, the individual horse was included as a random effect. All statistical analyses were performed using a commercially available software (SPSS statistics, release 27.0.0.0, IBM Corporation, Armonk, New York; R, release 4.1.2). A p-value < 0.05 was considered significant.

Results

In total, 115 Warmblood horses of 26 different breeds applied to the inclusion criteria (median age of 12 years; range, 5–29 years). Age group 1 included 42 horses (median, 8 years; range, 5–10 years), age group 2 comprised 40 horses (median, 13 years; range, 11–15 years), and 33 horses were allocated to age group 3 (median, 19 years; range, > 15 years). In total, 44 mares, 68 geldings and 3 stallions were represented. A total of 1637 teeth (1356 upper and lower incisors, 281 canine teeth) were included, and 203 teeth (24 incisors, 179 canine teeth) were either missing or only rudimentary existing and therefore not available for evaluation.

Overall frequencies of the CT features are shown in Table 1 and are grouped by tooth in Table 2. Descriptive statistics for all measurements are presented in Table 3. Descriptive statistics for the length of the pulp cavity and the angulation for each incisor per age group are presented in Table 4.

44.3% of all horses had normal incisors whereas 55.7% of the horses had mild changes in one incisor at least. Mild, moderate, or severe EOTRH was diagnosed in at least one incisor in 23.5%, 11.3% and 20.9% of all horses, respectively. Overall, 54.7% of the horses had normal canine teeth. In the remaining 43.3% horses, mild, moderate, or severe EOTRH was found in at least one canine tooth in 2.7%, 16.0% and 26.7% horses, respectively.

With regard to all investigated teeth, 868 teeth (53.0%) were classified as normal, whereas 769 incisors and canine teeth (47.0%) showed at least one abnormal CT criterion. By far, clubbing of the root was the most common abnormality (37.1% of all teeth), followed by hypercementosis (22.7% of all teeth). Less commonly seen were widening of the periodontal space at the apex of the root (10%) or at the anatomical root (8.3%) and resorption in the root (8.9%). The remaining changes were rare (abnormal pulp cavity, resorption in the crown, lysis of the lamina dura, root fracture). Loss of the periodontal space was not observed in any tooth. Overall, EOTRH was found in 27.1% of all investigated teeth. In general, mild changeswere more common in all investigated CT-criteria whereas moderate or severe changes were rare (Tables 1, 2).

In the lower jaw, hypercementosis and widening of the periodontal space at the root were significantly more frequent ($p = 0.004$ and 0.02), whereas clubbing of the root was more common in the upper jaw ($p = 0.009$). Frequencies of the other single CT criteria as well as EOTRH did not significantly differ between the lower and upper jaw ($p = 0.06$–0.83).

In canine teeth, resorption in the crown or root, widening of the periodontal space at the anatomical root or apex of the root, clubbing of the root and lysis of the lamina dura were significantly more common whereas hypercementosis was significantly more common in incisors ($p < 0.001$). Frequency of an abnormal pulp cavity, fracture of the root and EOTRH did not differ between incisors and canine teeth.

Table 1 Frequencies of computed tomographic findings in 1637 incisors and canine teeth of 115 Warmblood horses (EOTRH: equine odontoclastic tooth resorption and hypercementosis). | *Häufigkeit der computertomographischen Befunde in 1637 Schneide- und Hengstzähnen von 115 Warmblutpferden (EOTRH: equine odontoclastic tooth resorption and hypercementosis).*

CT CRITERION		ABSOLUTE FREQUENCY	RELATIVE FREEQUENCY
Resorption in the crown	Normal	1582	96.6%
	1–3 lesions of a size ≤ 3 mm	31	1.9%
	1 lesion > 3 mm or diffuse resorption	24	1.5%
Hypercementosis	No hypercementosis	1266	77.3%
	Hypercementosis with rippled tooth surface and a mildly blunted apex	260	15.9%
	Hypercementosis with clubbing and a tapering root	91	5.6%
	Hypercementosis with clubbing and a cylindric root	20	1.2%
Pulp cavity	Normal	1521	93.0%
	Closed	62	3.8%
	Lytic and/or containing gas	49	3.0%
Widening of the periodontal space at the apex of the root	Normal	1473	90.0%
	2–4 mm	135	8.3%
	> 4 mm	28	1.7%
Widening of the periodontal space at the anatomical root	Normal	1501	91.7%
	2–4 mm	109	6.7%
	> 4 mm	26	1.6%
Lamina dura	Normal	1592	97.3%
	Lysis	45	2.7%
Resorption in the root	Normal	1491	91.1%
	1–3 lesions of a size ≤ 3 mm	86	5.3%
	1 lesion > 3 mm or diffuse resorption	60	3.7%
Fracture of the root	No	1621	99.1%
	Yes	15	0.9%
Clubbing of the root without hypercementosis	No clubbing	1029	62.9%
	Clubbing with a tapering root	503	30.7%
	Clubbing with a cylindric root	105	6.4%
EOTRH	No EOTRH	1194	72.9%
	Mild	207	12.6%
	Moderate	84	5.1%
	Severe	152	9.3%

Table 2 Relative frequencies (%) of computed tomographic (CT) findings in 1637 incisors and canine teeth in 115 Warmblood horses (per tooth, *Triadan* and *Floyd* system). | *Relative Häufigkeiten (%) von computertomographischen (CT) Befunden in 1637 Schneide- und Hengstzähnen von 115 Warmblutpferden (pro Zahn, System nach Triadan und Floyd).*

CT CRITERION		101	102	103	201	202	203	301	302	303	401	402	403	104	204	304	404
Resorption in the crown	Normal	100	100	98.2	98.2	98.2	97.3	99.1	99.1	100	99.1	100	97.3	84.3	85.5	90.1	83.1
	1–3 lesions of a size ≤ 3 mm	0	0	0	0.9	1.8	1.8	0.9	0.9	0	0.9	0	1.8	5.7	5.8	5.6	12.7
	1 lesion > 3 mm or diffuse resorption	0	0	1.8	0.9	0	0.9	0	0	0	0	0	0.9	10	8.7	4.2	4.2
Hypercementosis	No hypercementosis	78.8	69.6	81.6	79.6	75.4	73.5	78.6	67.0	74.8	77.2	70.8	75.0	95.7	95.7	80.3	80.3
	Hypercementosis with rippled tooth surface and mildly blunted apex	14.2	26.1	11.4	15.0	18.4	20.4	14.3	24.1	14.4	15.8	18.6	16.1	2.9	4.3	11.3	15.5
	Hypercementosis with clubbing and tapering root	5.3	3.5	5.3	2.7	4.4	2.7	6.3	8.9	9.9	6.1	9.7	7.1	1.4	0	8.5	4.2
	Hypercementosis with clubbing and cylindric root	1.8	0.9	1.8	2.7	1.8	3.5	0.9	0	0.9	0.9	0.9	1.8	0	0	0	0
Pulp cavity	Normal	89.4	95.7	96.5	89.4	92.1	94.7	93.8	93.8	91.9	93.9	94.6	93.8	92.9	95.7	87.3	91.4
	Closed	6.2	2.6	1.8	8.0	4.4	0.9	6.3	4.5	3.6	4.4	3.6	1.8	1.4	1.4	5.6	2.9
	Lytic and/or containing gas	2.7	1.7	1.8	2.7	3.5	4.4	0	1.8	4.5	0.9	1.8	4.5	5.7	2.9	7.0	5.7
Periodontal space at the apex of the root	Normal	90.3	95.7	96.5	92.9	94.7	90.3	90.2	88.4	92.8	90.4	91.2	87.5	85.7	87.0	77.5	77.1
	2–4 mm	8.0	4.3	2.6	5.3	3.5	8.0	7.1	10.7	6.3	7.9	8.0	9.8	11.4	11.6	18.3	20.0
	> 4 mm	1.8	0	0.9	1.8	1.8	1.8	2.7	0.9	0.9	1.8	0.9	2.7	2.9	1.4	4.2	2.9
Periodontal space at the anatomical root	Normal	95.6	96.5	93.9	92.9	94.7	91.2	95.5	95.5	93.7	93.0	88.5	90.2	88.6	85.5	77.5	82.9
	2–4 mm	4.4	2.6	4.4	6.2	3.5	8.0	3.6	4.5	6.3	5.3	9.7	7.1	10	11.6	15.5	12.9
	> 4 mm	0	0.9	1.8	0.9	1.8	0.9	0.9	0	0.9	1.8	1.8	2.7	1.4	2.9	7.0	4.3
Lamina dura	Normal	96.5	100	99.1	99.1	99.1	96.5	99.1	100	95.5	99.1	96.5	96.4	94.3	97.1	91.5	90.1
	Lysis	3.5	0	0.9	0.9	0.9	3.5	0.9	0	4.5	0.9	3.5	3.6	5.7	2.9	8.5	9.9
Resorption in the root	Normal	97.3	96.5	91.2	95.6	89.5	90.3	99.1	94.6	93.7	95.6	92.0	84.8	85.7	84.1	76.1	74.6
	1–3 lesions of a size ≤ 3 mm	1.8	2.6	5.3	4.4	7.0	5.3	0.9	2.7	1.8	2.6	5.3	9.8	7.1	7.2	12.7	15.5
	1 lesion > 3 mm or diffuse resorption	0.9	0.9	3.5	0	3.5	4.4	0	2.7	4.5	1.8	2.7	5.4	7.1	8.7	11.3	9.9
Fracture of the root	No	99.1	99.1	99.1	98.2	99.1	99.1	100	100	98.2	100	98.2	100	100	100	94.4	100
	Yes	0.9	0.9	0.9	1.8	0.9	0.9	0	0	1.8	0	1.8	0	0	0	5.6	0
Clubbing of the root without hypercementosis	No clubbing	60.2	68.7	66.7	57.5	67.0	61.1	68.8	71.4	68.5	66.7	77.0	69.6	40	43.5	45.1	44.3
	Clubbing with tapering root	30.1	28.7	28.9	35.4	29.6	35.4	28.6	25.9	28.8	29.8	18.6	27.7	38.6	40.6	39.4	38.6
	Clubbing with cylindric root	9.7	2.6	4.4	7.1	3.5	3.5	2.7	2.7	2.7	3.5	4.4	2.7	21.4	15.9	15.5	17.1
EOTRH	No	77.0	68.7	77.2	77.9	71.9	74.3	77.7	67.0	72.1	75.4	70.8	68.8	75.7	76.8	66.2	67.6
	Mild	13.3	24.3	10.5	13.3	14.0	14.3	14.3	21.4	14.4	14.0	13.3	11.6	0	1.4	4.2	1.4
	Moderate	1.8	2.6	4.4	4.4	6.1	4.4	0.9	1.8	1.8	2.6	5.3	8.9	11.4	5.8	12.7	16.9
	Severe	8.0	4.3	7.9	4.4	7.9	7.1	7.1	9.8	11.7	7.9	10.6	10.7	12.9	15.9	16.9	14.1

Table 3 Descriptive statistics of the measurements on 1637 incisors and canine teeth of 115 Warmblood horses (*Triadan* and *Floyd* system): Median (MD), minimum value (Min), maximum value (Max). | *Deskriptive Statistik der Messungen an 1637 Schneide- und Hengstzähnen von 115 Warmblutpferden (System nach Triadan und Floyd): Median (MD), minimaler Wert (Min), maximaler Wert (Max)*

		Tooth (Triadan and Floyd system)															
Tooth		101	102	103	201	202	203	301	302	303	401	402	403	104	204	304	404
Angle (degree)	MD	137.2	135.8	133.7	137.9	135.7	133.9	167.2	170.5	168.1	168.9	170.1	167.3				
	Min	119.7	114.5	115.3	116.6	118.3	119.3	132.7	147.3	146.6	143.8	146.5	148.4				
	Max	149.8	154.7	153.0	153.9	149.6	175.9	185.6	194.9	187.5	182.0	187.4	187.2				
Length of pulp cavity (mm)	MD	6.1	6.5	6.2	6.1	6.6	6.2	6.2	6.6	6.7	6.3	6.6	6.9	4.9	4.8	5.6	5.6
	Min	3.6	4.9	3.9	3.8	4.7	4.7	4.6	5.0	5.3	4.1	3.1	5.3	3.3	1.2	0.0	3.9
	Max	7.6	7.8	7.8	7.5	8.0	7.6	7.6	7.9	8.2	7.6	7.9	8.4	6.4	6.1	8.2	7.0
Length of enamel labial (mm)	MD	5.0	5.0	4.0	4.9	5.1	4.0	4.9	2.6	4.5	4.9	4.8	4.4				
	Min	1.2	1.8	1.5	0.0	1.2	1.3	1.9	1.2	2.3	2.3	2.6	2.5				
	Max	6.8	6.6	5.7	6.8	6.6	5.6	6.2	5.2	5.7	6.4	6.6	6.0				
Length of enamel lingual/palatinal (mm)	MD	2.5	2.5	2.4	2.6	2.7	2.5	2.9	3.0	3.0	3.0	3.0	3.0				
	Min	0.0	0.0	0.6	0.0	0.4	0.0	1.1	1.5	1.3	1.4	1.4	1.4				
	Max	9.8	9.2	7.0	10.0	6.9	9.3	4.4	4.3	4.7	8.3	4.1	4.4				
Length of root labial (mm)	MD	2.1	2.6	2.9	2.2	2.7	2.8	2.4	2.6	3.0	2.4	2.7	3.1				
	Min	0.0	0.0	1.3	0.6	0.5	1.3	1.1	1.2	1.1	1.1	1.5	0.2				
	Max	3.6	4.8	4.6	9.7	4.9	4.9	4.1	5.2	4.4	4.0	4.6	8.4				
Length of root lingual/palatinal (mm)	MD	2.9	3.3	3.3	3.0	3.3	3.2	2.7	3.0	3.3	2.7	3.0	3.3				
	Min	1.0	0.5	1.7	1.1	0.5	1.2	1.5	1.6	1.5	1.3	1.5	1.6				
	Max	4.4	4.8	9.1	4.3	5.5	4.6	3.9	4.4	4.9	4.0	4.5	4.8				

Table 4 Descriptive statistics of the angle measurements on 1356 incisors as well as the length of the pulp cavity measurements on 1637 incisors and canine teeth of 115 Warmblood horses (Triadan and Floyd system), divided by age group: Median (MD), minimum value (Min), maximum value (Max). | *Deskriptive Statistik der Winkelmessung an 1356 Schneidezähnen und Messungen der Pulpalänge bei 1637 Schneide- und Hengstzähnen von 115 Warmblutpferden (System nach Triadan und Floyd), aufgeteilt nach Altersgruppen: Median (MD), minimaler Wert (Min), maximaler Wert (Max)*

			(Triadan and Floyd system)															
Tooth		Age group	101	102	103	201	202	203	301	302	303	401	402	403	104	204	304	404
Angle	MD	1	136.1	133.8	131.2	136.0	133.3	131.9	167.0	170.5	165.1	169.5	170.1	168.8				
		2	141.3	137.8	135.5	141.4	138.4	134.4	168.1	171.2	169.6	169.4	171.4	170.2				
		3	136.6	135.2	139.7	136.8	135.9	137.3	165.8	169.5	169.5	166.2	168.3	170.6				
	Min	1	121.9	114.5	119.3	123.3	118.3	119.6	150.9	154.0	145.6	150.4	153.0	154.1				
		2	128.5	121.4	115.3	124.7	126.7	119.3	154.7	155.5	151.8	157.2	154.1	153.9				
		3	119.7	121.3	123.5	116.6	123.3	124.8	132.7	147.3	147.1	143.8	146.5	146.5				
	Max	1	149.8	144.2	142.2	146.9	144.4	166.5	185.6	194.9	184.7	182.0	187.4	182.1				
		2	148.9	150.1	149.9	153.9	149.6	175.9	182.1	183.6	187.5	181.3	184.6	179.4				
		3	149.7	154.7	152.9	148.4	148.4	160.4	183.0	182.4	185.3	181.6	182.4	187.4				
Length of pulp cavity	MD	1	6.3	6.5	6.3	6.2	6.5	6.2	6.4	6.6	6.6	6.5	6.9	6.6	4.8	4.7	5.4	5.4
		2	6.3	6.7	6.2	6.25	6.8	6.4	6.4	6.8	7.0	6.5	6.7	6.7	5.3	5.1	6.0	6.1
		3	5.3	6.1	5.6	5.36	6.2	5.9	5.8	6.3	6.4	5.9	6.2	6.2	4.9	4.9	5.7	5.5
	Min	1	5.5	5.6	3.9	5.45	5.5	5.3	5.7	5.8	5.4	5.4	5.4	5.8	3.6	3.7	0	3.9
		2	5.1	6.1	5.5	4.8	5.5	5.5	5.2	5.4	5.9	5.0	4.9	5.8	4.5	4.3	3.4	5.4
		3	3.6	4.9	4.6	3.8	4.7	4.7	4.6	5	5.3	4.1	3.1	3.1	3.3	3.3	4.6	4.3
	Max	1	7.6	7.8	7.4	7.4	8.0	7.6	7.6	7.9	7.4	7.6	7.9	7.9	6.0	6	6.4	6.8
		2	7.3	7.8	7.8	7.5	7.8	7.3	7.2	7.7	8.2	7.4	7.6	7.9	6.4	6.1	7.2	6.8
		3	6.8	7.2	7.1	7.0	7.6	7.4	7.4	7.6	8.1	7.1	7.5	7.6	6.0	6.0	8.2	7

Groupwise comparison of frequencies of CT abnormalities between the first, second and third incisor revealed the following: hypercementosis, resorption in the root and EOTRH were significantly more common in the 2nd incisors compared to the 1st incisors, whereas clubbing was more commonly found in the 1st incisors compared to the 2nd incisors ($p = 0.0009$–0.02). If the 3rd incisors were compared to the 1st or 2nd incisors, resorption of the root only was significantly more common in the 3rd incisors ($p = 0.09$ and < 0.001). Additionally, lysis of the lamina dura was more common in the 3rd incisors compared to the 2nd incisors ($p = 0.04$).

The following correlations were significant: A weak to moderate positive correlation was found between age and severity of all CT features as well as severity of EOTRH ($r = 0.08$–0.56). Also, a moderate positive correlation was found between age and palatal/lingual and labial length of the root ($r = 0.43$ and 0.39), whereas correlation to angulation of the incisors was weak ($r = 0.04$). A negative correlation was found between age and length of the pulp cavity and the palatal/lingual and labial length of the enamel ($r = -0.25$, -0.3 and -0.59, respectively). A moderate positive correlation was found between EOTRH and abnormal pulp cavity, widening of the periodontal space at the anatomicalroot or apex of the root, lysis of the lamina dura and palatal/lingual and labial length of the root ($r = 0.3$–0.42). Although EOTRH also correlated significantly positively with angulation of the incisors and fracture of the root, correlation was weak ($r = 0.02$–0.12). Between EOTRH and length of the pulp cavity and the palatal/lingual and labial length of the enamel correlations were negative ($r = -0.2$, -0.36 and -0.39, respectively).

Finally, a linear forward and backward multivariate regression analysis confirmed a significant association between EOTRH and age, changes of the pulp cavity, widening of the periodontal space at the anatomical root and incisor group (central, middle, corner) ($p = 0.01 - < 0.001$).

Discussion

In this study, the overall prevalence of incisors affected by EOTRH – both at the level of the individual tooth as well as the horse – was considerably lower compared to previous radiographic studies. In particular, moderate and severe abnormalities were less common than previously described (*Henry* et al. 2017, *Rehrl* et al. 2018, *Rehrl* et al. 2022). These discrepancies can be at least partially explained by the different populations of horses included in these studies: while the current study examined Warmblood horses between 5–29 years of age, other studies that used radiographic images to diagnose EOTRH also included ponies (*Rehrl* et al. 2018, *Rehrl* et al. 2022) and Thoroughbreds (*Henry* et al. 2017, *Rehrl* et al. 2018, *Rehrl* et al. 2022) spanning a larger age range. Apart from the different populations of horses examined, the evaluation criteria and techniques used also differed between the current study and previously published studies using radiographic criteria to diagnose and categorize EOTRH. Although the scoring scheme developed for this study was based closely on previously published literature for radiographic evaluation of EOTRH (*Rehrl* et al. 2018), it is likely that the different imaging modalities and scoring criteria further contributed to the observed differences in EOTRH prevalence. Radiographic imaging of teeth to evaluate EOTRH presence offers a good overview of the entire tooth and the surrounding area, as well as good comparison to neighboring teeth at relatively low cost. However, this type of diagnostic imaging is limited when it comes to overlaying structures especially around the tooth root and is less sensitive in determining mild differences in tooth density.

Typically, intraoral, and laterolateral radiographs are taken for EOTRH diagnostics, but these images do not allow for evaluation of the teeth in more than one plane as CT studies do. Other authors used the hemisphere model to better evaluate the teeth in question (*Stoll* et al. 2011, *Rehrl* et al. 2018). A very recent study showed that numerous radiographically healthy incisors displayed lesions upon macroscopic inspection (13.7%) and micro-CT analysis (58.1%) (*Albers* et al. 2022). Previous studies found that tooth resorption was significantly more frequent than hypercementosis (51.1% and 7.6% of evaluated incisors respectively) (*Henry* et al. 2017). Contrary to these observations, our study shows that hypercementosis is much more frequent than resorption of the root or crown, even if widening of the periodontal space is interpreted as external inflammatory resorption. Furthermore, our study did not find any indication of loss of periodontal space on any of the examined incisors. In this case, using CT rather than classic radiographs might help avoid false positive diagnoses of tooth resorption since there are fewer overlapping structures, and differences in tooth density can be assessed more accurately. First signs of EOTRH are typically found on the palatal side of incisors in the upper jaw, and on the lingual side of incisors in the lower jaw (*Staszyk* et al. 2008, *Schrock* et al. 2013b), but these early signs are not necessarily detectable by radiographic imaging (*Albers* et al. 2022). In the current study, these early signs of EOTRH were not categorized separately in the CT scoring scheme.

Nevertheless, they could have contributed to the higher incidence of hypercementosis observed here. To definitively determine the diagnostic sensitivity of radiographic images compared to CT studies, further studies are necessary.

Hypercementosis and widening of the periodontal space at the root of incisors and canine teeth were observed significantly more often in teeth of the lower jaw, whereas clubbing of the root was more common in the upper jaw. Other recent studies have come to contradictory conclusions regarding the occurrence of hypercementosis in the upper jaw compared to the lower jaw; while our findings align with those of *Rehrl* et al. (2022) they stand in contrast to previous studies stating that resorption and hypercementosis are more frequent in teeth of the upper jaw (*Henry* et al. 2017).

Comparing incisors to canine teeth, we observed that hypercementosis was more frequently present on incisors, whereas resorption of the crown, widening of the periodontal space at the anatomical root or apex of the root, clubbing of the root, and lysis of the lamina dura where more commonly found in canine teeth. Hypercementosis can be interpreted as a mechanism to stabilize teeth. EOTRH as a periodontal disease entity leads to instability of the affected tooth. Hypercementosis represents an increase in the volume of the tooth in the alveolar compartment, thus a higher stability of the tooth in the alveolar compartment could be achieved. Canine teeth are neither in occlusion when the jaw is closed nor when it is moving, this could help explain why canine teeth are less frequently affected by hypercementosis. Other studies examining EOTRH on canine teeth specifically have yet to be published.

When comparing the individual incisors, we found that hypercementosis, resorption of the root, and EOTRH were more commonly found on 2nd incisors compared to 1st incisors. Excluding the 2nd quadrant, hypercementosis was also seen more frequently in the 2nd than in the 3rd incisors; and resorption of the root was less common in the 2nd compared to the 3rd incisors. Apart from the 4th quadrant, EOTRH were more commonly found on 2nd incisors compared to 3rd incisors. These findings are in agreement with previous studies concluding that EOTRH-associated changes are most frequent in 2nd incisors (*Rehrl* et al. 2022).

However, our results do not align with those of *Henry* et al. (2017), who found that the 3rd incisor of the lower jaw was most often affected by hypercementosis.

Clubbing of the root was also unevenly distributed between incisors, but in contrast to hypercementosis it was found more commonly on 1st incisors than on 2nd incisors, and excluding the 3rd quadrant it was also found more commonly on 1st incisors than on 3rd incisors. In this case, the correlation between tooth age and occurrence of EOTRH holds true when comparing the incisors to each other; the 1st incisors are the oldest of the incisors, which led *Rehrl* et al. (2022) to hypothesize that a higher incidence of EOTRH would be expected in 1st incisors since tooth age is a critical factor for developing EOTRH. Even though overall EOTRH was not observed more frequently in 1st incisors in the current study, the higher rate of clubbing could in fact be an early sign of EOTRH in these teeth.

In the current study, we found that resorption of the root was significantly more common in 3rd incisors than in 1st or 2nd incisors. Similar observations have been made previously in a study where external replacement resorption was more common on 3rd incisors than on 1st or 2nd incisors (*Henry* et al. 2017). In addition to these individual criteria, EOTRH was significantly associated with incisor group in the final multivariate model in the present study.

In agreement with previous radiographic studies, our current CT-based study found that there was a significant positive correlation between age and all individual CT criteria as well as overall EOTRH (*Henry* et al. 2017, *Hole* und *Staszyk* 2018, *Rehrl* et al. 2018, *Rehrl* et al. 2022). At the level of the tooth, we observed that the length of the anatomical root (both measurements in longitudinal section palatal/lingual and labial) increased with increasing age, whereas the length of the pulp cavity, as well as the palatal/lingual length of the enamel decreased slightly. These findings align with the conclusions of other studies (*Staszyk* et al. 2006b, *Schrock* et al. 2013c).

Similarily, angulation of the incisors increased with age in the present study. While some older studies reported angle measurements of approx. 180° between the incisors of the upper and lower jaw in young horses, and lower angles in older horses, more recent and more detailed studies are missing (*Habermehl* 1981, *McMullan* 1983, *Muylle* et al. 1999, *Listmann* et al. 2017, *Kau* et al. 2020). Age-related differences in the angulation of the incisors can be at least partially explained by the changes to the surrounding boney structures that are triggered by biomechanical stimuli when chewing (*Schrock* et al. 2013b). Indeed, our study showed a moderate positive correlation between occurrence of EOTRH in incisors and increasing angulation of the teeth. These findings correspond to those of a previous study that reported a lower angulation of the incisors in horses affected by EOTRH (*Staszyk* et al. 2008).

Finally, the multivariate regression analyses performed in the current study did not confirm a significant effect of the different tooth measurements on the presence of EOTRH, with only the age of the horse showing a significant association. Further studies with repeat examination of the subjects would be necessary to definitively address which changes are age dependent and which are directly associated with EOTRH.

In this study, we found a significant increase in EOTRH occurrence with decreasing length of the pulp cavity and enamel of the palatal/lingual or labial side of the tooth. These findings support the conclusion of previous studies that there is a correlation between EOTRH and teeth having a short reserve crown (*Staszyk* et al. 2008). The intra-alveolar parts of the tooth (i.e. the reserve crown and the root) function as the area of attachment of the periodontal ligament, which plays an important role in dampening the forces exerted when chewing (*Staszyk* und *Gasse* 2005, *Schrock* et al. 2013c). If the area of attachment of the periodontal ligament is reduced, the ligament can become overstressed ultimately leading to periodontal necrosis (*Staszyk* et al. 2006a). Experimental studies with rats have shown that periodontal compression does in fact lead to local necrosis which can progress to tooth resorption at a later stage (*Brudvik* und *Rygh* 1993). Accordingly, researchers have hypothesized that increased periodontal stress can promote the development of EOTRH in equines as well (*Staszyk* et al. 2008). However, the multivariate regression model applied to these criteria in the current study did not reveal any significant association but could be indirectly represented by the significant effect of age in EOTRH development.

Multiple studies have reported that inflammation of the periodontal ligament precedes the occurrence of resorptive lesions of the calcified substance of the tooth.

Periodontal inflammation was observed at the subgingival level and in the middle of the reserve crown, with apical spreading as the disease progress (*Klugh* 2004, *Baratt* 2007, *Caldwell*, *Staszyk* et al. 2008). A finite element analysis showed stress- peaks in the periodontal ligament, in the bone of the alveolar crest, as well as in the palatal/lingual side slightly occlusal of the apex of the root. These affected regions correspond to the observed sites of early EOTRH lesions (*Schrock* et al. 2013b). The results of our study support these findings because changes to the periodontal ligament at the anatomical root but not the apex of the root were significantly associated with EOTRH. However, we did not find that EOTRH frequently occurred together with loss of the periodontal space as previously reported (*Baratt* 2007, *Caldwell*).

In the present study, changes of the pulp cavity were significantly associated with the presence of EOTRH in the single factor analysis as well as the multivariate regression analysis. Changes of the pulp cavity and their significance in regards to EOTRH have long been discussed, because resorptive lesions are known to break in to the pulp cavity (*Staszyk* et al. 2008, *Earley* et al. 2011, *Smedley* et al. 2015). Even though *Smedley* et al. (2015) found that changes of the pulp cavity were significantly associated with EOTRH, they also found that resorptive lesions with secondary hypercementosis originated from the surface of the tooth rather than the pulp cavity. Overall, changes of the pulp cavity were only rarely observed in the current study, with an equal distribution between a closed pulp cavity and resorptive lesions.

Superficial resorptive lesions that break into the pulp cavity were not found.

Lysis of the lamina dura did not correlate significantly with EOTRH, in accordance with older studies suggesting that changes to the lamina dura represent normal ageing symptoms (*Staszyk* et al. 2008) or can be triggered by other diseases (*Smedley* et al. 2015).

There are some limitations of the current study that need to be addressed. First, dental history of the horses was unknown, which means the results could be biased towards horses without diseases of the incisors or canine teeth. Furthermore, even though the correlations found in this study were significant, the correlation was only weak to moderate. We would therefore suggest repeating the CT examinations in a larger population with a higher prevalence of EOTRH.

Conclusion

Computed tomographic changes of the incisors and canine teeth are common and age-related in Warmblood horses. Therefore, treatment of EOTRH should not be based on diagnostic imaging alone, but always in combination with a thorough clinical examination. Although computed tomography has proven to be a valuable tool to evaluate changes in equine incisors and canine teeth, it remains to be determined if it will be routinely used as the diagnostic method of choice for EOTRH due to increased expenditures compared to radiographic imaging.

Authors' declaration of interests

No competing interests have been declared.

Ethical animal research

Research ethics committee oversight not required by this journal: retrospective analysis of clinical data.

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