# ADVANCES IN EQUINE DENTAL AND SINONASAL DISORDER RESEARCH

EDITED BY: Padraic Martin Dixon, Richard Reardon and Lieven Vlaminck

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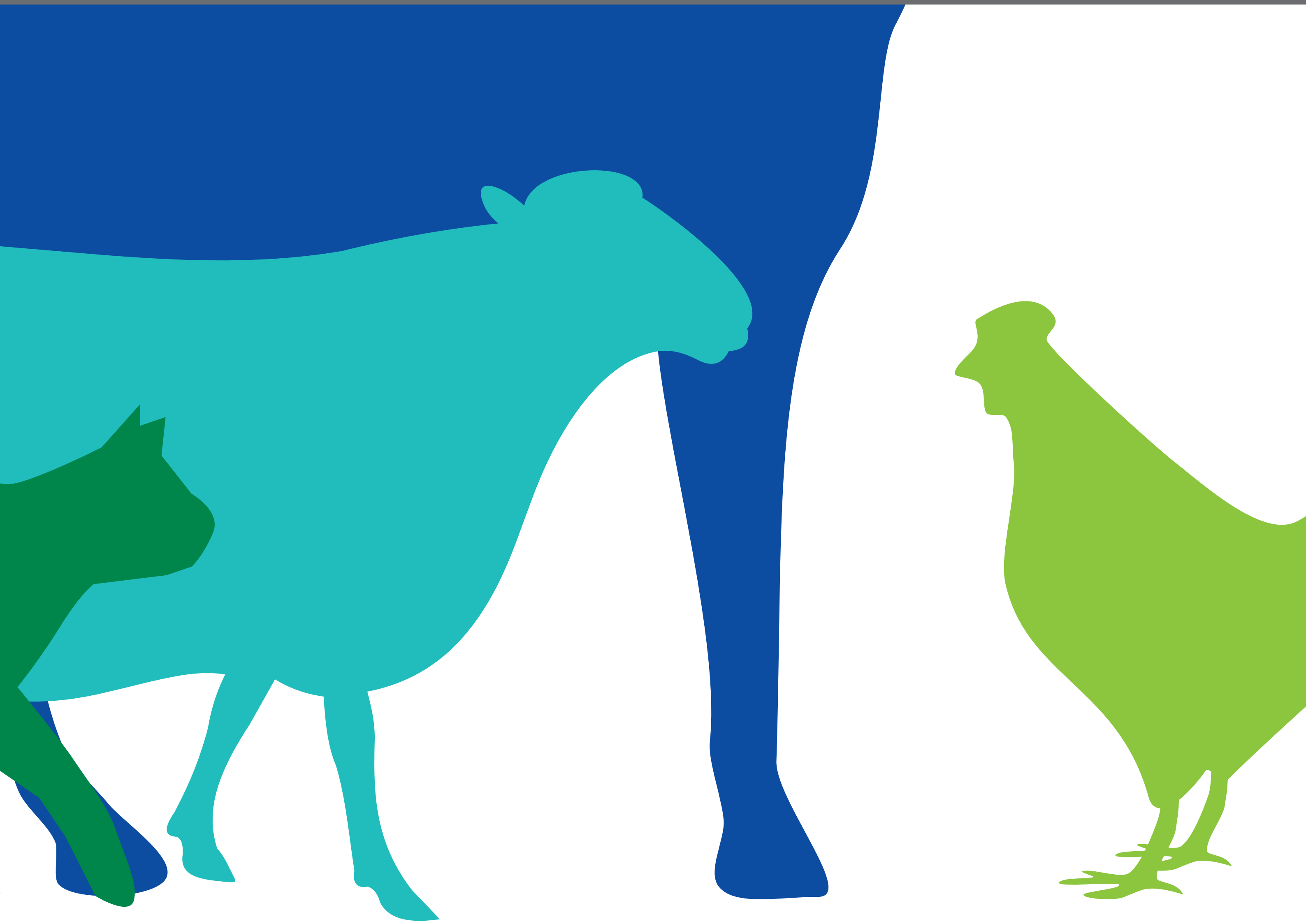

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# ADVANCES IN EQUINE DENTAL AND SINONASAL DISORDER RESEARCH

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EDITORIAL
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# Editorial: Advances in Equine Dental and Sinonasal Disorder Research

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**Keywords: equine sinonasal disorders, equine sinusitis, equine sinus osteitis, equine sinonasal imaging, equine dentistry, equine dental fractures**

**Editorial on the Research Topic**

**Advances in Equine Dental and Sinonasal Disorder Research**

This collection in the veterinary dentistry and oromaxillofacial surgery speciality section of Frontiers in Veterinary Science presents 10 peer-reviewed research articles that investigate many important topics in equine dentistry and sinonasal disorders.

Three of the papers used computed tomography (CT) to investigate equine sino-nasal disorders that are often caused by dental disease.

A study by Dixon, Puidupin et al. showed that horses with sinus disease have significant inflammation of the bones adjacent to the paranasal sinuses. This sinusitis-related osteitis can explain the presence of epiphora, soft tissue facial swellings and the increased maxillary bone radionucleotide uptake in sinusitis cases. Osteitis and distortion of the maxillary septal bulla or infraorbital canal can also explain the difficulty in fenestrating the maxillary septal bulla in some horses with sinus disease.

A study of 300 horses with sinus disease that all underwent CT examinations, included 100 consecutive referred cases from three different equine referral centers (Dixon, Barnett, et al.). This study identified dental sinusitis and chronic primary sinusitis as the main types of sinus disease. The rostral maxillary sinus (94.7% involvement) and the ventral conchal sinus (87% involvement) were the most commonly affected compartments. Notably, this study also showed involvement of the nasal conchal bullae in 56% of horses with sinus disease.

Sinonasal drainage obstruction of their normal mucus secretions can occur in miniature horse breeds, possibly due to developmental distortion of their sino-nasal bony structures (Vlaminck et al.). This study by Vlaminck et al. described the diagnosis of 7 such cases, including by CT, in young (mean age 2.2 years) American miniature horses and miniature Shetland ponies. Their successful treatment was by fenestration of the dorsal conchal sinus into the nasal cavity *via* nasofrontal osteotomies followed by temporary catheterisation of the sino-nasal fistula to maintain patency.

A further CT study by Liuti et al. examined the angulation and age-related dental drift of the rostral (second premolar tooth; Triadan 06) and caudal (third molar tooth; Triadan 11) mandibular and maxillary equine cheek teeth in horses of different ages. The study showed much higher angulation in the mandibular vs. the maxillary teeth, and in the third molar teeth (Triadan 11 s) vs. the second premolar teeth (Triadan 06s). The angulation of most teeth did not decrease with age contrary to expectations. The caudal (distal) angulation of the second premolar teeth (Triadan 06) clinical crowns might indicate that distal drift occurs in these teeth, but in fact all teeth drifted mesially with age. Further understanding of age-related dental drift and dental angulation may help elucidate the causes and treatment of the very common and painful disorder of equine cheek teeth diastema.

A retrospective study by Gergeleit and Bienert-Zeit found clinically significant post-extraction complications following 6.6% ($n = 20$) of 302 mandibular cheek tooth extractions. Horses

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developing complications were younger than those not developing complications and the Triadan 07s and 09s were the most commonly affected teeth. Alveolar sequestration was the most prevalent complication, occurring in 18/20 horses, with complete alveolar sequestration occurring in some cases. Post-extraction mandibular fistula formation occurred in 5/20 cases and mandibular abscessation in 4/20 cases. All cases were successfully treated, including by sequestrectomy and wound debridement with some cases taking up to 5 months to resolve.

There has been debate on the presence and frequency of communications between the discotemporal joint (DTJ) and the discomandibular joint (DMJ) in normal equine temporomandibular joints (TMJ). A study by Pimentel and Carmalt examined for the presence of communications between these two compartments in 20 normal horses. No physiological communication between the two compartments was identified. However, 2/40 joints had an acquired communication between the DTJ and DMJ. This finding is clinically relevant when considering the use of local anesthesia or medication in these compartments.

Abnormalities of equine maxillary cheek teeth infundibula are common, mainly varying degrees of developmental cemental hypoplasia with later acquired caries that may predispose to fracture or apical infection of these teeth. This article by Pearce and Brooks is the first peer-reviewed study on the long-term clinical and oral endoscopic finding in horses undergoing infundibular caries treatment. The described infundibular restoration technique was found to be safe and most restorations lasted for many years (including for over 10 years in some). Only 1.3% of treated teeth later developed fractures or apical infection thus supporting the value of this technique.

Three studies examined non-traumatic equine cheek teeth fractures: fissure fractures ($n = 2$) and gross fractures ($n = 1$).

An *ex vivo* study by Pollaris et al. assessed whether the presence of fissure fractures or other anatomical features influenced the development of gross fractures when mechanical pressure was applied to the occlusal surface of these teeth. Resistance to fracture was found to vary between different sites on the occlusal surface of healthy equine cheek teeth, and the presence of fissures further decreased fracture resistance.

A 3-year longitudinal study by Pollaris et al. of 36 horses with cheek teeth fissure fractures assessed for long-term changes in these teeth, including determining if any of these fissure fractures later converted to gross fractures. The study found that over time, the fissure fractures could remain unchanged, disappear, become longer, shorter, change in configuration or in color. Gross fractures (all partial crown fractures, with none resulting in direct communication with the pulp) were found to be more likely when: fissure fractures were present, in mandibular (rather than maxillary) teeth and on the lingual (rather than the buccal) side of the tooth.

A study of 300 horses with 486 non-traumatic gross cheek teeth fractures by Dixon, Kennedy et al. showed the maxillary teeth to be most commonly affected, including 1st and 2nd pulp horn ("slab") fractures and caries-related infundibular fractures. Mandibular cheek teeth 1st and 2nd pulp fractures were the most common mandibular cheek teeth fractures. Almost half of affected horses had no clinical signs, the others mainly having signs caused by apical infection or oral pain. The stable remnants of fractured teeth were not extracted in 60% of cases.

It is hoped that this collection of studies will encourage further basic and clinical equine dental and sinonasal research. The increasing number of standing CT systems will allow further studies of these anatomically complex areas with multiple overlapping structures, that until recently have had restricted two-dimensional imaging by radiography. The increasing use of quality oral endoscopes will allow further and more detailed oral examinations such as the recognition cheek teeth fissure fractures and allow further studies on the progression or regression of such lesions, as found in one of the above studies. Finally, the increasing numbers of American and European Board Specialists in equine dentistry will hopefully increase the pool of researchers in this field.

## AUTHOR CONTRIBUTIONS

This editorial was written by PD and edited by RR and LV. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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# Complications Following Mandibular Cheek Tooth Extraction in 20 Horses

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The objectives of this retrospective study were to describe the prevalence and characteristics of post-operative complications that occur following equine mandibular cheek tooth extractions and to assess for possible associated risk factors. Clinically significant post-extraction complications necessitating repeat referral developed following 20/302 (6.6%) mandibular cheek tooth extractions. Horses developing complications were younger than the overall population having mandibular cheek teeth extractions and the most commonly affected teeth were the Triadan 07 s and 09 s. Alveolar sequestration was the most prevalent complication, occurring in 18/20 horses (90%), with the complete alveolus sequestering in some cases. Post-extraction mandibular fistula formation occurred in 5/20 cases (25%) and mandibular abscessation in 4/20 cases (20%). All cases were successfully treated, including sequestrectomy, and wound debridement with some cases taking up to 5 months for resolution. Anatomical features of the equine mandibular alveoli and bone appears to make them more prone to develop extensive sequestration compared to published complications on maxillary alveolar bone. This requires good pre-operative examination including diagnostic imaging to identify cases of higher risk and thorough risk disclosure toward horse owners as well as owners' compliance.

**Keywords: equine, exodontia, fistula, tooth sectioning, sequestrum**

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## INTRODUCTION

Dental extractions are standard procedures in horses with diseased cheek teeth, especially apical infections, but they are associated with a higher prevalence of complications compared to other commonly performed surgical procedures (1–3). However, the development of newer instrumentation for less invasive techniques, improvements in training and advancements in sedation and analgesia have negated the need for standard dental repulsions under general anesthesia and have made dental surgeries less debilitating for horses (4).

Reported post-extraction complication rates differ remarkably among studies. The highest complication rates are reported for repulsion of cheek teeth under general anesthesia with up to 80% post-operative complications (2, 5) whereas standing oral extractions have considerably lower complication rates of 4–20% (2, 6, 7) making this the preferred method whenever possible.

Despite the above advances, complications still occur with equine cheek tooth extractions with an apparently higher prevalence with mandibular (18.1%) than maxillary (9.7%) cheek teeth extractions (3).

The aims of this study were to describe clinical and demographic findings of horses that developed clinically significant complications following mandibular cheek tooth extraction, and to describe possible risk factors for their development. This knowledge will hopefully allow objective information on the risks of mandibular cheek teeth extraction to be disseminated.

## MATERIALS AND METHODS

Clinical records of all equine cheek tooth exodontias performed between January 2014 to December 2019 at the Equine Clinic, University of Veterinary Medicine Hannover were examined. Data obtained included demographic and case details, Triadan position of affected teeth, number of teeth extracted and the extraction technique. Diseased cheek teeth that were readily extracted (either by hand or within 15 min with use of forceps) were not included in these data.

Maxillary or mandibular cheek teeth extraction records were separated, and mandibular extraction records were reviewed for the presence of post-operative complications. From these records, case details and clinical findings from the initial general and oral examinations, radiographic findings, diagnosis, surgical procedure and post-operative findings were thoroughly examined and tabulated. If teeth could not be extracted *per os* with forceps, the number and types of additional exodontia procedures were recorded. Where teeth were not extracted intact, post-operative radiographs were used to confirm complete cheek tooth extraction.

A complication associated with mandibular cheek tooth removal was defined as a case that: required additional post-extraction treatments in addition to standard alveolar swab changes; had delayed healing (>8 weeks for complete gingival epithelization); significant increase in treatment costs and/or moderate to severe post-extraction discomfort. Minor complications including reduced food intake or mild swellings that resolved within 2–3 days following extraction that were considered clinically insignificant and did not cause delayed alveolar healing were not included in this study.

### Standard Post-operative Management

Horses received flunixin meglumine (Flunidol® CP-Pharma Handelsgesellschaft mbH, Burgdorf, Germany) twice daily 1.1 mg/kg bwt for 3 days followed by 0.55 mg/kg for two days. Horses received systemic antibiotics (trimethoprim sulfadiazine: Synutrim® Vétoquinol GmbH, Ismaning, Germany) 30 mg/kg bwt twice daily pre-operatively only if they had a pre-existing mandibular fistula, moderate to severe pain on mandibular palpation or during mastication or if an additional technique to oral extraction was required. In these horses, antibiotic treatment was started ∼12 h before the operation and continued for 5–10 days following the extraction depending on the clinical course.

Following extraction, the alveoli were lavaged with water with mild pressure to remove debris and pus and a surgical swab impregnated with medical grade honey (Mielosan® CP-Pharma Handelsgesellschaft mbH, Burgdorf, Germany) was placed in the alveoli. The alveolus was examined oroscopically and by digital palpation, and the initial swab was replaced in our clinic, usually at 2 days post-surgery, and weekly afterwards by the referring veterinarian until there was almost complete alveolar healing.

Follow-up information on post-operative complications associated with the underlying disease or the extraction technique was obtained from the clinical records, the referring veterinarian or by informal telephone interviews with owners.

## RESULTS

### Case Overview

A total of 880 cheek teeth extractions including 578 (65.7%) maxillary and 302 (34.3%) mandibular teeth were performed in 561 horses, at 653 dental procedures (**Figure 1**). Patients included 48.9% females, 48.1% geldings, and 3% stallions of a mean of 13.3 ± 6.1 years old (range 3–29 years) with a similar age distribution for maxillary (mean 13.5 ± 5.9 years) and mandibular cheek teeth (mean 13 ± 6.7 years).

Twenty of the 302 (6.6%) extracted mandibular cheek teeth developed clinically significant post-operative complications necessitating re-referral back to this clinic (**Table 1**) and all required longer post- extraction treatment than usual. During this period, no horses were referred back to us because of maxillary alveolar sequestration. The prevalence of post-extraction complications was highest for mandibular Triadan 07 s (7/55 horses; 12.7%) and 09 s (7/101 horses; 6.9%). Horses developing complications were considerably younger (mean 7.3 ± 3.7 years; range 3–14 years) than all horses undergoing mandibular tooth extraction (mean 13 ± 6.7 years).

### Initial Clinical Findings and Diagnostic Imaging Findings of 20 Cases Developing Complications

Ten of the 20 horses that developed complications had mandibular swellings with four of these also having an external draining tract (fistula) (**Figure 2**). Radiography with use of a probe showed the fistulas to be associated with Triadan 07 s apices ($n = 3$) and Triadan 06 ($n = 1$). Infection-related apical malformation and enlargement was found in eight horses (**Figure 3**).

The diagnosed dental problem necessitating exodontia in these 20 teeth was apical infection ($n = 6$), endodontic diseases ($n = 8$, including due partial fractures and pulpitis) and periodontal diseases ($n = 6$, including diastemata and tooth displacement).

Horses with apical infections were a mean of 5.5 (range 3–8) years old and had infected Triadan 07 s ($n = 4$) and 06 s ($n = 2$). Horses with endodontic and periodontal disease were a mean of 9 (range 4–14) years old with affected teeth in all Triadan positions, except Triadan 08.

### Surgical Techniques

Oral extraction with forceps in deeply sedated horses, following a mandibular nerve block and local infiltrative anesthesia was initially attempted in all cases. This technique was successful at the initial surgery in 11/20 horses (55%) taking between 30 min and 4 h, including preparation time. However, additional techniques (described below) were required in 7/20 horses (35%) (**Figure 4**). In two other horses, the affected tooth was extracted per *os* at a second surgery.

Intraoral sectioning of the tooth under endoscopic guidance was performed during the first procedure in three horses and in one horse at a second procedure which allowed complete extraction in two of these four cases. Tooth sectioning was performed with a motorized instrument and a 3 mm diameter double cut carbide burs of different length. Teeth were sectioned

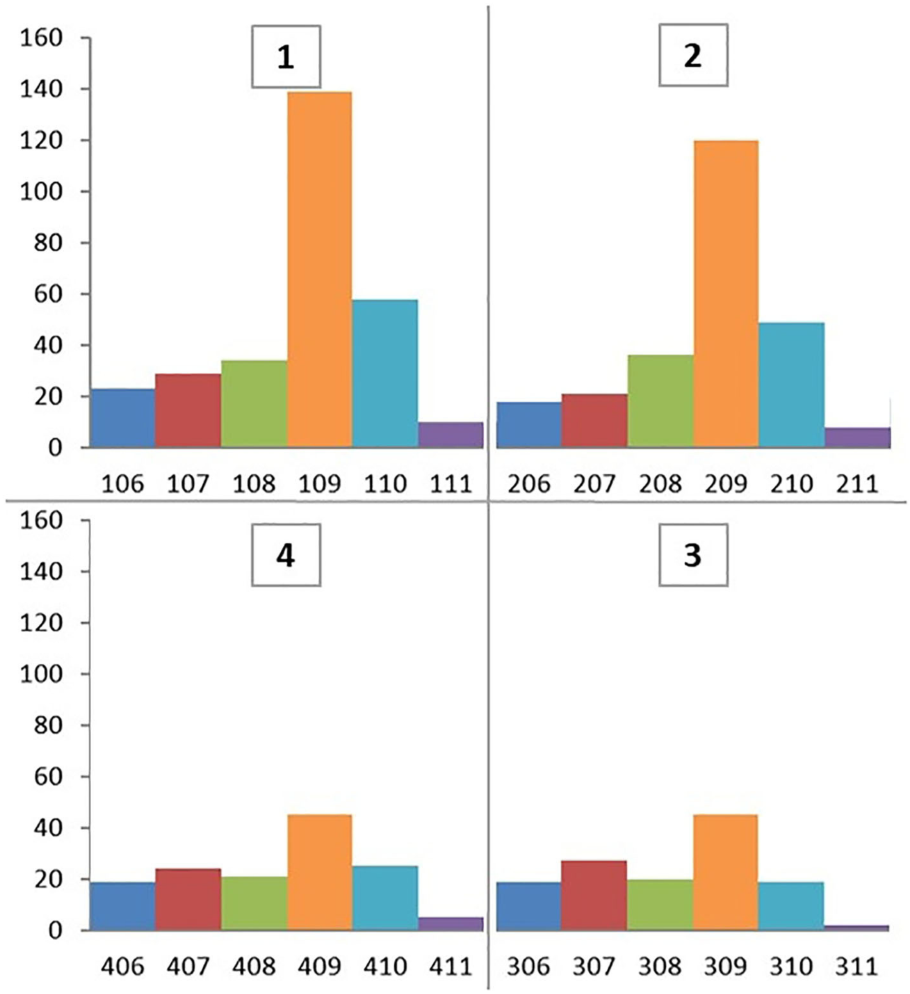


**FIGURE 1 |** Triadan positions of 880 cheek teeth extracted between January 2014 and December 2019.

on a lingual to buccal transverse direction between pulp horns 1 and 2 in order to create a gap and separate the mesial and distal part of the tooth (**Figure 5**). Intraoral water lavage was used to cool the instrument and the tooth during sectioning. In the two cases where sectioning failed the tooth was successfully repulsed via the preexisting fistula in one case and the other case had a minimally invasive buccotomy to successfully remove the remaining dental fragment. A minimally invasive buccotomy was successfully utilized during the first procedure in one of the remaining cases and a screw extraction during a second procedure in one other case. Overall, five horses required a second surgery 2–3 days following the first attempt to complete the exodontia (**Figure 4**).

## Post-operative Complications

The most prevalent significant post-operative complication necessitating re-referral, occurring in 18/20 horses (90%) was alveolar bone sequestration with consequent delayed alveolar healing. The overall prevalence of clinically significant alveolar sequestration following mandibular extractions was 6% (18/302). Other complications included post-operative mandibular abscess and fistula formation ($n = 7$). Abscess formation at the buccotomy site ($n = 1$) developed within 2 days of surgery. Following drainage and routine wound lavage, it healed completely by secondary intention within 3 weeks. Mandibular abscesses drained spontaneously ($n = 2$) two and seven weeks following the tooth extraction or were incised under ultrasonographic guidance ($n = 2$) 1 week and 4 months, respectively, following the tooth extraction (**Figure 6**).

Alveolar healing problems usually became clinically obvious 1–2 weeks post-extraction. These disorders were detected by the referring veterinarian during routine post-extraction examinations or by the owners recognizing enlarging and painful mandibular swellings and problems in these horses when eating (slow chewing, quidding, or inappetence). All 20 horses were referred back for treatment at this clinic, 2–8 weeks following their initial discharge.

**TABLE 1 |** Case details for horses with post-operative complications following mandibular cheek tooth removal.

| No. | Age (years) | External swelling† | Draining tract† | Triadan | Underlying disease | Tooth deformity | First surgery | Second surgery | Complications |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 13 | NO | NO | 409 | Fractured crown | YES | Sectioning | Buccotomy | Sequestrum |
| 2 | 4 | YES | NO | 407 | Pulpitis, Displacement | YES | Buccotomy | n.a. | Buccal abscess, Sequestrum |
| 3 | 13 | NO | NO | 407 | Fractured crown, Pulpitis | NO | Extraction | Extraction root fragment | Fistula, Sequestrum |
| 4 | 4 | NO | NO | 410 | Diastemata, Periodontal disease | NO | Extraction | n.a. | Sequestrum |
| 5 | 4 | NO | NO | 309 | Pulpitis | NO | Extraction | n.a. | Sequestrum |
| 6 | 14 | NO | NO | 410-12 | Displacement, Periodontal disease | NO | Extraction | n.a. | Sequestrum, Abscessation mandible |
| 7 | 6 | NO | NO | 409 | Diastemata, Displacement, Periodontal disease | YES | Extraction | n.a. | Sequestrum, Abscessation mandible |
| 8 | 7 | YES | NO | 406 | Periodontal disease after extraction of 405 | NO | Extraction | n.a. | Sequestrum, Fistula |
| 9 | 10 | YES | YES | 306 | Periodontal disease after extraction of 305 | NO | Extraction | n.a. | Fistula post extraction 305 |
| 10 | 3 | YES | NO | 406 | Apical infection | YES | Extraction | n.a. | Sequestrum |
| 11 | 6 | NO | NO | 306 | Apical infection | NO | Extraction | n.a. | Sequestrum |
| 12 | 4 | YES | NO | 307 | Pulpitis, Apical infection | YES | Extraction | n.a. | Sequestrum |
| 13 | 11 | NO | NO | 309 | Fractured crown, Pulpitis | NO | Extraction | Sectioning, Screw-extraction | Sequestrum |
| 14 | 8 | YES | NO | 307 | Apical infection | NO | Extraction | n.a. | Sequestrum, Fistula |
| 15 | 13 | NO | NO | 409 | Fractured crown, Pulpitis | NO | Extraction, Sectioning | n.a. | Abscessation mandible |
| 16 | 5 | YES | YES | 407 | Apical infection | YES | Extraction, Sectioning, Repulsion | n.a. | Sequestrum |
| 17 | 4 | YES | YES | 407 | Apical infection | YES | Extraction | Repulsion | Sequestrum |
| 18 | 7 | YES | YES | 307 | Apical infection | YES | Extraction, Repulsion | n.a. | Sequestrum |
| 19 | 10 | YES | NO | 309 | Diastemata, Displacement, Periodontal disease | NO | Extraction | Extraction | Sequestrum, Abscessation mandible |
| 20 | 13 | NO | NO | 409 | Pulpitis | NO | Extraction | n.a. | Sequestrum, Fistula |

†*On initial presentation; n.a., not applicable.*

Sequestration of the alveolus was diagnosed by oral examination and using lateral oblique radiographs in 18/20 cases (**Figure 7**). The size of alveolar sequestrae varied from small fragments (up to 3 mm wide and <5 mm in length) with some other areas of alveolar healing occurring, to sequestration of the entire alveolus in four horses (**Figure 8**). Mandibular abscessation and fistula formation varied from fistula a few millimeters wide to extensive skin sloughing (**Figure 6**, right).

Treatment consisted of repeated sequestrectomy of demarcated loosened alveolar bone fragments, wound debridement, mandibular fistula curettage and non-steroidal anti-inflammatory drugs as required. Systemic antibiotics (trimethoprim sulfadiazine, and metronidazole in some cases) were administered based on microbiological findings in 17/20 cases with clinical discomfort, pyrexia, or evidence of osteomyelitis. Microbiological examination revealed a high prevalence of gram negative obligatory anaerobic bacteria (especially Fusobacterium and Prevotella species) together with *Actinobacillus* and *Streptococcus* species among others. Antibiotic administration was continued until there was an obvious clinical improvement usually for 5–10 days.

If intra-alveolar swabs (impregnated with honey or metronidazole) did not prevent gross alveolar food contamination, a temporary, superficial silicone implant (HS-VPS Hydro Putty Soft® Henry Schein Deutschland GmbH, Hannover, Germany) was used. Once there was an onset of good alveolar healing, horses were discharged from the clinic and thereafter had their progress checked weekly, either by us or the referring veterinarian. Most horses stayed in the hospital for ∼5–7 days until discharge, but two were hospitalized for almost 3 weeks at the owners' request. Complete healing was achieved

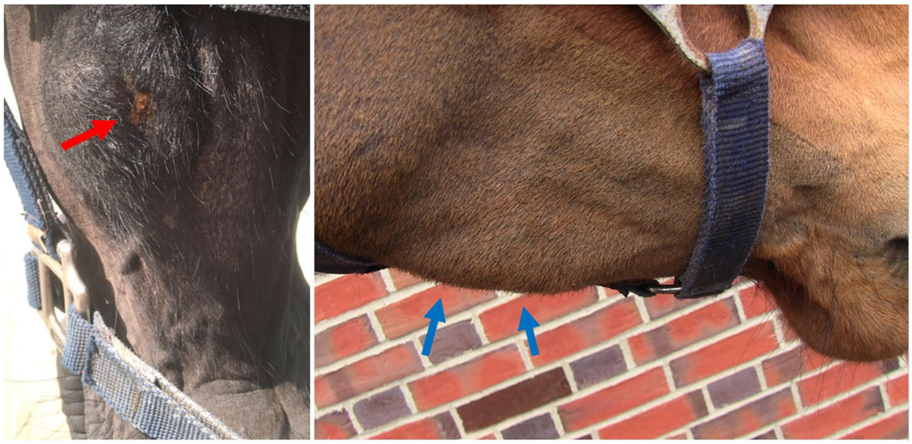

**FIGURE 2 |** Swelling of the left mandible with a purulent external draining tract (left, red arrow, Horse No. 18). A firm swelling of the right mandible (right, blue arrows, Horse No. 16). Both horses had apical infections.

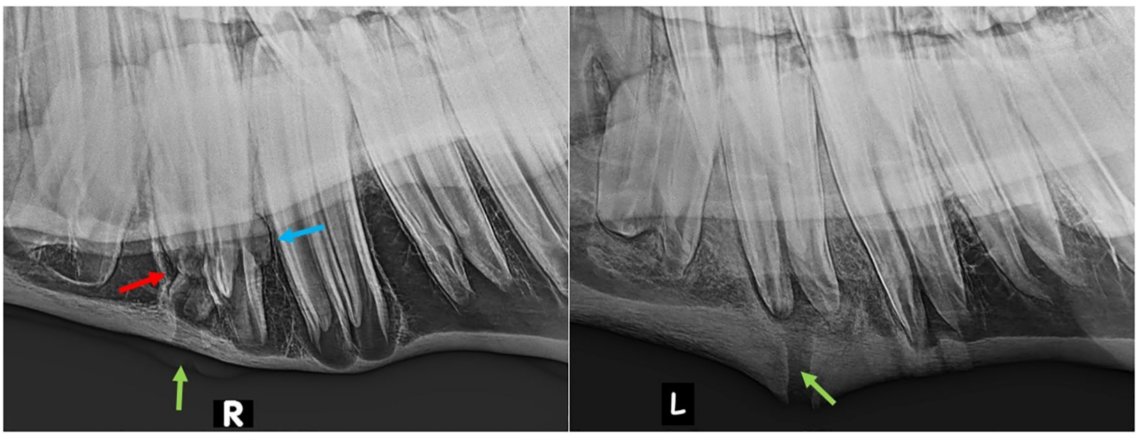


**FIGURE 3 |** Lateral oblique radiographs of the mandibles of two horses with apical infection. Left (Horse No. 16): External swelling and fistula from the mesial aspect of the 407 (green arrow). The mesio-distal aspect is markedly malformed (red arrow) and there is also a radiopaque enlargement on the distal aspect of the tooth (blue arrow). Right (Horse No. 18): External swelling and fistula from the mesial root of the 307 (green arrow).

in all cases by a median time of 3 months post-surgery (range 2–5 months). In the more complicated cases that took longest to heal, the costs to treat the complications were significantly higher than the costs for the tooth extraction and perioperative hospitalization itself.

## DISCUSSION

Our clinical impression, that significant post-operative complications associated with mandibular cheek tooth extraction are relatively common has been supported by this study.

Kennedy et al. (3) recently described an increased likelihood of disturbances in alveolar healing following mandibular as compared to maxillary cheek teeth exodontia, especially for mandibular Triadan 06-08 teeth. Apical infections, repulsion technique and horses of younger age were risk factors for post-operative complications (3). From our results, we can draw some similar conclusions.

Teeth extracted because of apical infections that later developed post-operative alveolar sequestration were most prevalent for mandibular Triadan position 07 in young horses (mean 5.5 years) in this study. These findings correlate well with a study by Dixon et al. (5) who found horses with cheek teeth apical infections were a median age of 5 years, with mandibular cheek teeth 07 and 08 most commonly involved. Theories why these teeth positions were so frequently infected soon after eruption include haematogenous infection of enlarged 'eruption cyst' that were possibly caused by cheek teeth impaction between adjacent teeth (8) or due to prolonged retention of deciduous cheek teeth remnants. However, in contrast to the study population from Kennedy et al. (3) mandibular Triadan 08 s post-extraction complications were not recorded in our study although similar numbers of Triadan 07 s and 08 s were extracted (55 and 47

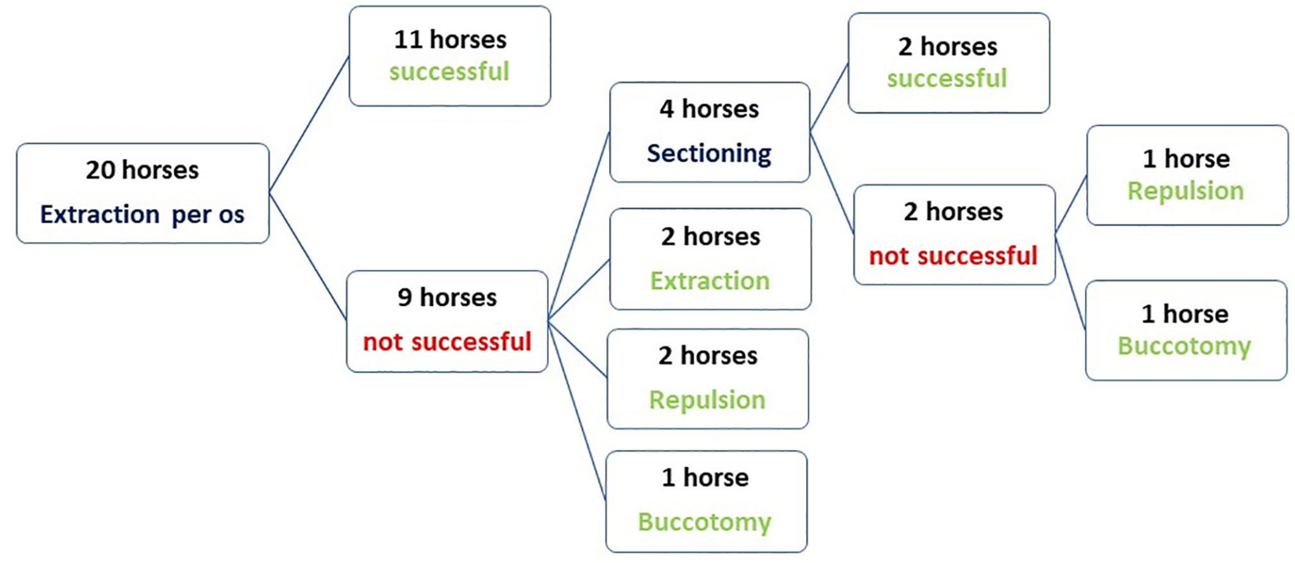


**FIGURE 4 |** Flow chart showing the techniques used for exodontia of mandibular cheek teeth in 20 horses that later developed post-operative complications.

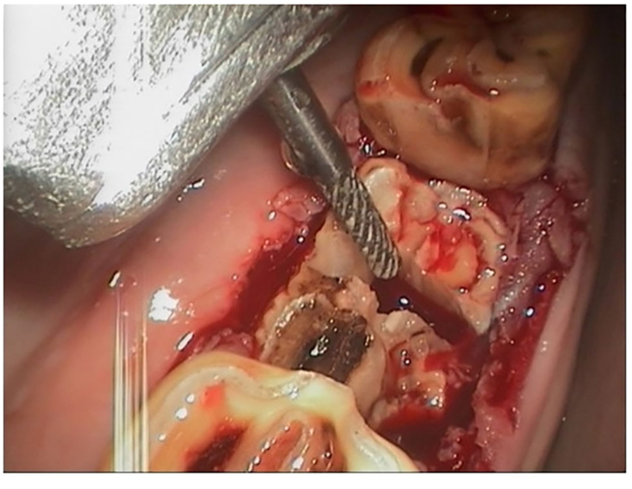

**FIGURE 5 |** Intraoral sectioning of a 407 under endoscopic control after the crown fractured during oral extraction. The bur is used to section the tooth in a lingual to buccal (transverse) direction to allow separate extraction of the mesial and distal parts of the tooth (buccal is to the left).

teeth, respectively). In contrast to Kennedy et al. (3), this study found the Triadan 09 s to most commonly (7/20) develop post-extraction problems.

Extraction of apically infected mandibular cheek teeth, especially in young horses, is complicated by their very extensive, and largely intact periodontal membranes (some loss at infected apex), that firmly attach their long reserve crowns to the alveoli (6). Increased surgical time, more elaborated extraction techniques, and application of higher forces are often necessary for exodontia in such cases. Extraction, especially elevation, is made more difficult if apical inflammation related deformation of the roots makes this area larger than the remaining alveolus (**Figure 3**, left). Rarely in chronic cases, these inflammatory processes may even apparently lead to ankyloses of the apex to the mandibular cortex (5), although such dental ankylosis of deciduous teeth, with a number of suggested causes is a relative common condition in children (9).

Appropriate pre-operative radiography is necessary to detect contour changes that could later complicate the extraction procedure and to help plan the most favorable extraction technique. Nonetheless, a standard series of two-dimensional radiographs of the mandible will not fully visualize apical contour changes that expand in a more latero-medial direction. This may increase the risk of underestimating the extent of tooth and alveolar bone deformation. Therefore, computed tomographic imaging should be considered in selected cases, including those with proliferative apical changes that would help with planning the surgical procedure and help to predict the post-operative course.

Following exodontia of mandibular cheek teeth with exostoses in this study, we would recommend that if there is no sufficient progress in loosening the tooth using the standard protocol with elevators and spreaders, pre-operative diagnostic images should be critically reassessed for any findings that could complicate the procedure. For example, in horse no. 16 retrospective examination of the pre-extraction radiographs indicate that oral extraction was likely to fail due to apical enlargement (**Figure 3**, right). Direct sectioning of this tooth after it was loosened without repeated attempts at elevation may have diminished the extent of post-operative sequestration. We conclude that prolonged oral extraction should not be performed unless some loosening and elevation of the tooth is occurring (independent from surgery time), and an alternative technique should be used

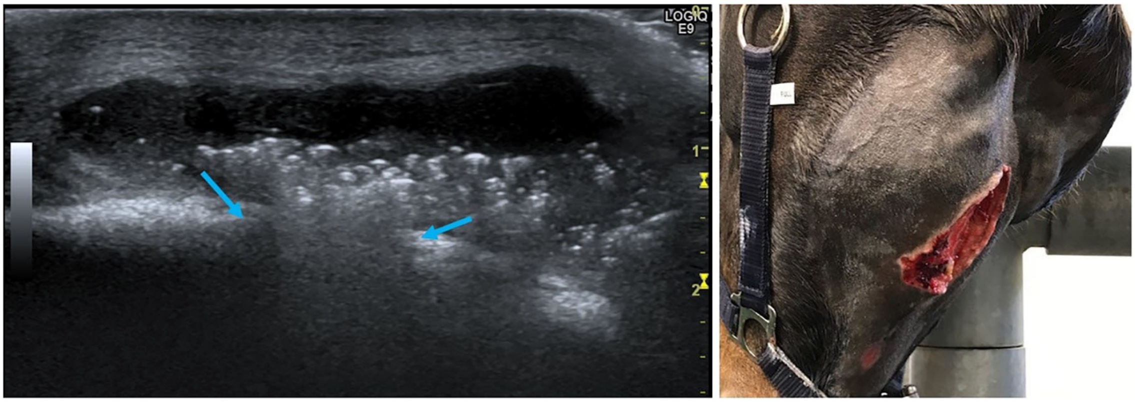


**FIGURE 6 |** Left (Horse No. 14): Ultrasonographic image of mandibular abscess formation after extraction of a 307 due to apical infection. The bone contour is interrupted (blue arrows) and the abscess presents as an anechogenic fluid-filled cavity with heterogeneous hyperechogenic spots. The skin is still intact (upper side of the image is ventral). Right (Horse No. 20): Extensive skin sloughing has occurred 7 weeks after 309 extraction and mandibular abscess formation.

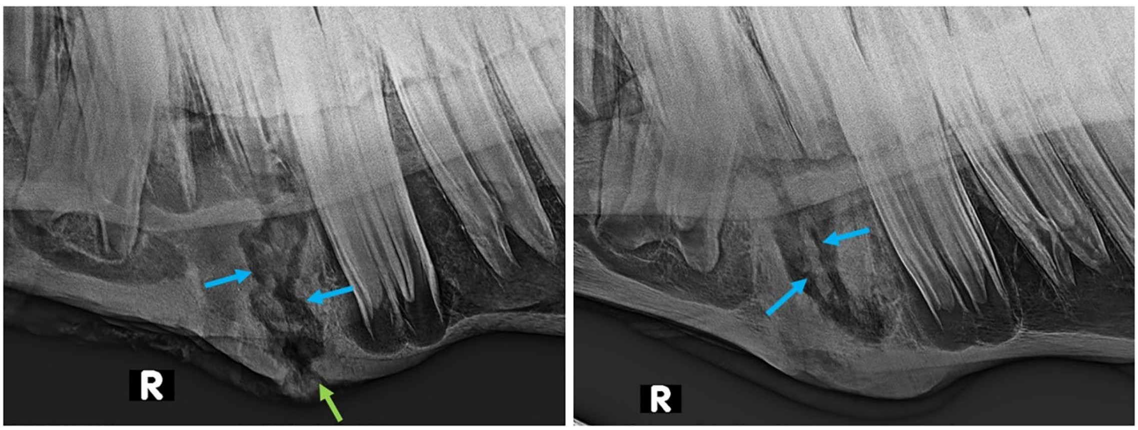


**FIGURE 7 |** Lateral oblique radiographs of the mandibles of two horses after extraction of 407 s, showing demarcated sequestra (blue arrows) in both. Left (Horse No. 16): External swelling and fistula (green arrow) are still present 10 weeks post-extraction. Right (Horse No. 17): Marked enlargement of the mandibular bone is present 8 weeks post-extraction.

to prevent tooth fracture and unnecessary damage to the alveolus and surrounding mandibular bone.

Oral extraction should always be the first method of choice, as several studies have proven the lowest complication rates for this approach (2, 6, 7, 10). However, pre-existing or exodontia-related tooth fractures can make oral extraction impossible (11) and necessitate another extraction method such as minimally invasive lateral buccotomy, intraoral sectioning with a surgical bur or repulsion. Occlusal fissure lines have been frequently identified in equine cheek teeth (12) but to communicate with the pulp in only 23% of cases (13). Such cases may contribute to endodontic diseases and crown fractures as well as to fractures during oral extraction.

We speculate that the more rectangular shaped mandibular cheek tooth as compared to the squarer shaped maxillary cheek tooth makes the former more prone to damage during extraction. Under latero-medial forceps forces, a mandibular cheek tooth cannot "rotate" as well as a maxillary cheek tooth. Not only is a mandibular cheek tooth at higher risk of fracture of the clinical crown with subsequent remaining of the anatomical crown and roots, the extractors may also apply more forces on to the alveolus. The production of bony micro-fractures may cause a diminished blood supply, devitalization, and later sequestration of alveolar bone. Human mandibular bone is a denser structure with a poorer blood supply than maxillary bone (14). If this also applies to horses, it probably further decreases the ability of mandibular bone to recover from exodontia damage.

Following extraction, the alveolar bone is further likely to undergo a diminished blood supply from the damaged or locally absent overlying periodontal membranes. This risk increases if oral extraction is not successful and more invasive exodontia techniques are required.

The most common secondary exodontia technique used in cases where *per os* extraction with forceps was not successful in

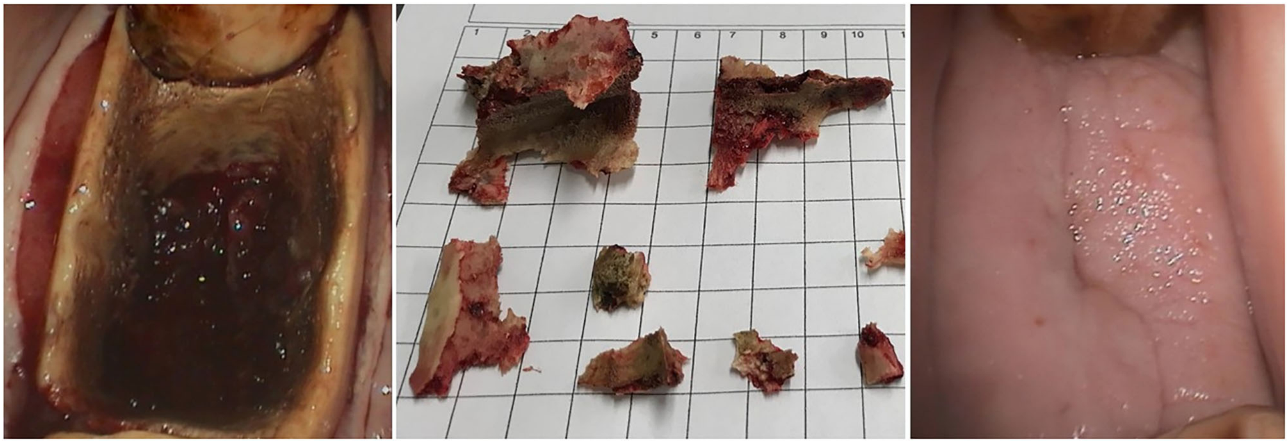


**FIGURE 8 |** Left: Oral endoscopic view of alveolar sequestration after a 407 extraction (Horse No. 16) by sectioning and repulsion (buccal is to the left). The devitalized bone fragments (middle image) required several treatments for removal. Right: Healing was almost complete after 4 months of additional treatment following exodontia (buccal is to the left).

fully extracting the tooth was intraoral dental sectioning under endoscopic control. Dental sectioning requires good equipment and teamwork, knowledge and experience including a reliable anesthetic protocol. Nonetheless, complications can occur if the horse is not sufficiently chemically restrained or if the alveolus or adjacent soft tissue are damaged directly by the bur or indirectly by conduction of thermal necrosis from the bur. These injuries can damage local blood supply and also provide an entry portal for microorganisms. These areas are also more prone to sequestrate and, if sequestrae are retained in the non-healing alveolus, may predispose to a localized osteomyelitis. Adjunctive water-cooling may offset the risk of thermal necrosis.

Alveolar sequestration was the most common (90%) post-operative complication in this study. Rice and Henry (7) described a sequestration prevalence of 2.4% after oral extractions following partial coronectomy and an overall complication rate of 3.6% (7). Considering that our cohort represents a prevalence of clinically significant sequestration in 18/302 (6%) mandibular cheek teeth in total, the prevalence is 2.5 times higher. Partial coronectomy appears to help loosen the tooth more efficiently and to allow elevation with less force compared to standard oral extraction methods. This may help reduce the prevalence of sequestration. However, the study of Rice and Henry compromised mainly of maxillary cheek teeth extractions. It appears from the current study that maxillary cheek teeth exodontia with subsequent alveolar sequestration is of less clinical concern and will often resolve with minimal effort or even spontaneously as also found by Kennedy et al. (3). Maxillary alveoli have naturally a better draining capacity as wound secretion and small sequestrae will fall out due to gravity. In contrast, empty mandibular alveoli provide a blind ending pocket in which microorganisms and sequesters can remain and promote an ongoing infection in the previously damaged alveolus (3). It is important to remove sequestra in all cases as antibiotic therapy and lavage alone nearly always fails to result in complete resolution of clinical signs and healing of the alveolus (11).

Post-operative complications occurred with all extraction methods in this study. No direct correlation between surgical time, final extraction method and severity of complications was found. One would anticipate a higher complication rate for longer and more complicated dental surgeries. However, one horse (No. 14, an 8 years old Warmblood gelding) where the apically infected 307 was extracted in <30 min, required continued removal of sequestrated bone fragments for over 4 months before complete healing occurred. In contrast, another 8 years old Warmblood gelding from the original cohort of extraction cases, which also had a 307 extracted, via sectioning and repulsion in a surgery that lasted about 4 h, did not develop any post-operative complications. These different responses indicate that the complication rate is not only associated with the extraction method and the course of the surgical procedure, but also with the stage and severity of the underlying disease or a combination thereof. Differences in the host's immune response and in microbial challenge may also influence the development of post-extraction infections (3). Albeit every dental surgery is invariably a contaminated procedure, mandibular bone abscess formation caused by apical infection probably further increases the risk of post-operative sequestration due to high bacterial burdens and focal osteomyelitis. The bacteremia identified during equine dental extractions is not necessarily clinically relevant (15), but it may increase the risk for local complications. Kennedy et al. (3) questioned the efficacy of culturing these sites but suggested that it may be useful in cases where osteomyelitis is identified (3).

The aftercare of the patient and the alveolus likely has an important impact on alveolar healing, although Caramello et al. (2) did not detect any significant association between alveolar packing and delayed alveolar granulation. Currently, there is no objective consensus on the optimal management of equine post-extraction alveoli. Nevertheless, regular alveolar examinations and packing changes, at least weekly post-surgery, are advisable to hopefully reduce microbiological overgrowth and to detect delayed healing at an early stage. Our clinical impression is that alveolar packing with swabs is more effective than silicone implants in cases without fistula formation. Swabs appear to allow for better drainage of secretions and give less resistance to sequestrae separation, leading to improved alveolar healing, but these assumptions need to be proven by clinical studies. There is no objective data on the best type of material to impregnate surgical swabs for alveolar packing. Kennedy et al. (3) used packing with metronidazole and broad-spectrum antibiotics but this did not prevent post-extraction complications in 5.9% of 407 mandibular cheek tooth extractions (3). Therefore, swab impregnation with antibiotics appears to give similar results to the use of medical grade honey (6.6% clinical alveolar post-extraction problems) for the routine packing of alveoli. Considering that antibiotic resistance is increasing, the use of such antibiotic dressings should be limited to cases with a specific indication for antibiotic therapy (16).

Limitations of this study include the incomplete comparison of the outcome for maxillary and mandibular cheek teeth exodontia. A complete evaluation of the post-operative outcome of maxillary cheek teeth extractions would be required to put the general risk factors into perspective. A direct comparison of the underlying dental disease necessitating exodontia, extraction techniques and outcome for all mandibular cheek teeth removals (complications vs. no complications) would further contribute to assessing risk factors for post-extraction complications. Furthermore, due to the retrospective design of this study there was incomplete follow-up information for cases with minor complications resolving spontaneously or treated by the referring veterinarian.

Complications associated with mandibular cheek tooth removal not only escalate the treatment costs, they may also cause more serious morbidity than the initial problem. The treatments to correct these post-extraction problems are often more time-consuming and more difficult than for the original underlying disease. Consequently, it is essential that a thorough clinical and radiographic examination is initially performed in order to decide on the optimal extraction technique. Where the oral extraction process is not proceeding as planned, the radiographs should be reviewed and/ or advanced imaging such as computed tomography sought. Moreover, the risks of such extractions should be disclosed to the owner before the procedure and they should be advised how to recognize post-extraction complications. Increasing our knowledge of possible risk factors for these complications through studies like this and future similar studies will hopefully help to decrease the complication rates.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the animal study because the data used in this study are based on clinical data generated for accountancy and documentation purposes. Our research does not involve any regulated animals, and there were no scientific procedures performed on animals of any kind. For this reason, formal approval by an ethical committee was not necessary under the provisions of the German regulations. Written informed consent for participation was not obtained from the owners because Retrospective analysis of clinical data. No identifiable animal and human data included.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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ORIGINAL RESEARCH
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# A Computed Tomographic Assessment of Osteitis of Sinus Bony Structures in Horses With Sinonasal Disorders

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**Background:** Computed tomographic (CT) imaging has shown some horses with sinonasal diseases to have changes in their sinus bony structures. Scintigraphic and clinical evidence of sinus osteitis have also been reported. However, no study has objectively examined for the presence and degree of osteitis in equine sinonasal disease.

**Objectives:** To assess for the presence and extent of osteitis of sinus-related bony structures by examination of CT images of horses with clinically and sinoscopically confirmed unilateral sinonasal disease.

**Study Design:** Retrospective examination of CT images of horses with confirmed, mainly chronic (>2 month duration) unilateral sinus disease of different etiologies.

**Methods:** Bone thickness at designated sites of the maxillary bone ($n = 3$), frontal bone ($n = 1$), infraorbital canal ($n = 2$), and bony nasolacrimal duct ($n = 1$) were measured, as were the maximal diameters of the infraorbital canal and the bony nasolacrimal duct on both affected and control sides. Maxillary bone density (in Hounsfield Units) was also assessed bilaterally. Bone thickness was compared between affected and controlled sides using paired statistical tests.

**Results:** Bone was significantly thicker in the affected sinuses compared to the control sides at the three maxillary bone sites (all, $P < 0.001$) and at both infraorbital bone sites (both, $P < 0.001$), but not at the two most dorsal sites examined, i.e. frontal bone ($P = 0.188$) and bony nasolacrimal duct ($P = -0.260$) sites. Infraorbital canal and bony nasolacrimal duct diameters were significantly wider in the affected as compared to the control sides ($P < 0.001$ and $P = 0.002$, respectively). Maxillary bone density did not differ significantly between the affected (mean = 1,075 HU, SD = 230.01) and control (mean = 1,100, SD = 200.71) sides ($t_{(58)} = -1.03$, $P = 0.306$).

**Main Limitations:** Possible variation in selecting measurement sites. Variation in the severity and chronicity of sinonasal disease between horses.

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**Conclusions:** Osteitis and enlargement of paranasal bony structures commonly occurs in horses with sinonasal disease and can explain the clinical presence of ipsilateral diffuse soft tissue facial swelling, epiphora, and scintigraphic evidence of bone inflammation in sinonasal disease.

**Keywords: horse, equine sinus disease, sinonasal imaging, computed tomography, sinus bone inflammation, sinus osteitis**

## INTRODUCTION

Equine sinonasal disorders are often chronic (>2 months duration), usually unilateral disorders, with multiple etiologies that are non-responsive to conservative therapy (1–4). It is difficult to identify the underlying cause of the sinus disease in most cases by clinical examination and therefore diagnostic imaging including radiography (5), scintigraphy (6, 7), and computed tomography (CT) (8–15) are usually required for this purpose. Imaging is also used to identify which sinus compartments are affected and to identify intercurrent nasal disorders, including the presence of sino-nasal fistula, inspissated exudate, bone sequestrae, and infected nasal conchal bullae and hence these disorders could be more correctly termed sinonasal disorders (3, 4, 9, 12–14). Such imaging information allows appropriate treatment to be performed, which can include dental extraction and removal of exudate from the affected sinuses or nasal cavities.

An important early equine CT study, largely examining dental and alveolar changes in 18 cases of sinus disease by Henninger et al. (9), noted maxillary bone thickening and infraorbital canal distortion in most horses. A later CT study also noted maxillary bone osteitis in a horse with sinusitis (10). A recent large CT study showed changes in infraorbital canal mineralization, size, shape, and/or position in 78% of horses with sinus disorders (15).

Scintigraphic imaging has shown that some horses with primary and dental sinusitis have unexplained, often focal areas of increased radioactive uptake (IRU), including of the maxillary bones, in addition to the alveolar bone changes in horses with dental sinusitis (7). Horses with the two most common types of sinus disease, i.e., primary and dental sinusitis do not have firm facial swellings that are often present in horses with sinus cysts, intra-sinus growths, and facial suture exostoses. However, some cases of primary and dental sinusitis develop unexplained low-grade, diffuse facial swellings (**Figure 1**), and others develop epiphora (**Figure 2**) (1, 2, 4). The latter has been assumed to be due to nasolacrimal duct compression from intra-sinus exudate accumulation.

Sinoscopy of horses with sinonasal disease sometimes shows thickening and calcification of the maxillary septal bulla (MSB) (formerly misnamed the *ventral conchal bulla*) (**Figure 3B**) and/or enlargement of the infraorbital canal (**Figures 3B**, **4**). These two changes can cause difficulties or even prevent fenestration of the MSB, which is necessary to access the rostral maxillary sinus (RMS) and ventral conchal sinus (VCS), the compartments most commonly affected with sinus disorders (Authors personal observations).

The introduction of CT imaging for human chronic rhinosinusitis circa 30 years ago, allowed detailed assessment of sinus drainage pathways and of mucosal swelling not possible with radiography. It also clearly showed that in addition to mucosal inflammation, remodeling of the underlying bones occurred in many patients, that was histologically confirmed as a non-septic osteitis (16, 17). Since then, multiple studies have shown osteitis to occur with human chronic rhinosinusitis with a reported prevalence of 51% in all patients and of 76% in those that


**FIGURE 1 |** This horse with left-sided primary sinusitis has a soft tissue swelling over its left maxillary region that pits on digital pressure, indicating subcutaneous oedema. Maxillary bone sinusitis-related osteitis could explain such soft tissue facial swellings.

underwent sinus surgery, although the etiology and pathogenesis of this osteitis remain unclear (18–21). Many studies have examined the relationship between the degree of osteitis and the clinical severity and prognosis of human rhinosinusitis, especially in chronic refractory cases, and a number of sinus osteitis grading scales have been developed for this purpose (19–21). In addition to assessing bone thickness and the imaging appearance of sinus osteitis by CT, other authors have shown that an increase in bone density (H.U. values) in human sinusitis correlates with the degree histopathological bone changes present (22).

In contrast, no studies appear to have objectively assessed for the presence or extent of osteitis in equine sinonasal disease. The aim of this project was to retrospectively examine CT images of horses with unilateral sinonasal disease for evidence of osteitis of their maxillary and frontal bones, bony nasolacrimal duct and infraorbital canals by assessment of bone thickness, infraorbital canal, and bony nasolacrimal duct diameters, and of maxillary bone density, using the unaffected contra-lateral sinuses as controls.

## MATERIALS AND METHODS

A retrospective examination was made of 60 randomly selected CT images of heads from horses of mean age 11.7 years (median age 11, range 5–26 years) with confirmed paranasal sinus disease (many also had intercurrent ipsilateral nasal disease)

**FIGURE 2 |** Horse with left sided sinusitis and ipsilateral epiphora. Such sinusitis-related epiphora were assumed to be caused by intra-sinus pressure from accumulated exudate, but may be caused by osteitis and partial obstruction of the nasolacrimal duct.

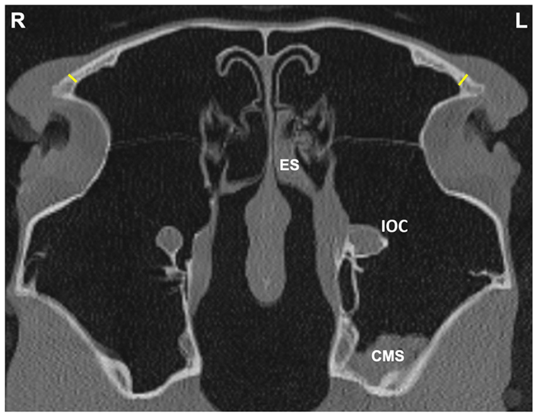


**FIGURE 4 |** Transverse CT image of head of a horse with left-sided sinus disease, obtained at the level of the frontal sinus (FS). A small amount of hypoattenuating material is present within the left (L) caudal maxillary sinus (CMS) and ethmoidal sinus (ES) and there is a widened infraorbital canal (IOC). Frontal bone (FB) thickness was measured at a single site 1 cm dorsal to the junction between the medial aspect of the orbital rim and the caudal aspect of the nasal bone on the affected and contra-lateral sides (yellow lines).

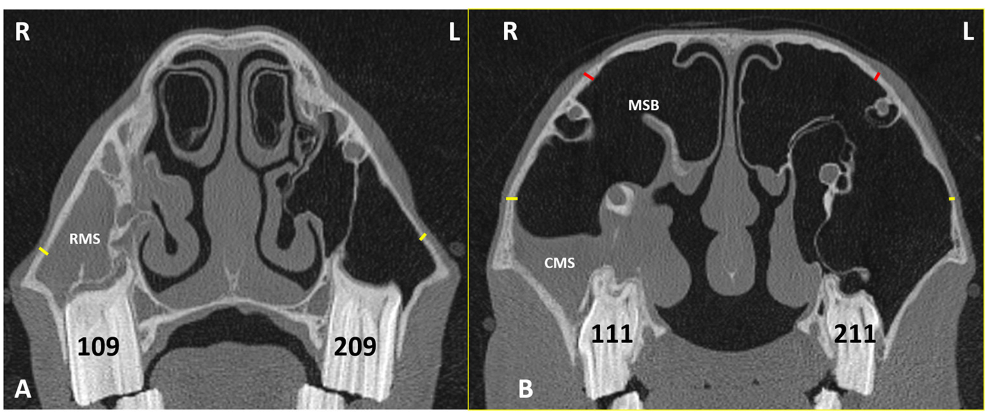


**FIGURE 3 |** Transverse CT images of head of a horse with right-sided sinusitis obtained at the level of Triadan 09s **(A)** and Triadan 11s **(B)**. Hypoattenuating fluid is present within the right RMS and CMS. The right maxillary septal bulla (MSB) shows thickening of its bone and the overlying mucosa **(B)**. Maxillary bone measurement at the rostral maxillary sinus (RMB) **(A)** were obtained 2 cm dorsal to the facial crest on the affected right (R) and control left (L) sides (yellow lines). Maxillary bone measurement at the caudal maxillary sinus **(B)** were obtained 2 cm dorsal the maxillary crest (yellow lines) (CMBV) and also 1 cm dorsal the nasolacrimal canal (red lines) (CMBD) on the affected right (R) and control left (L) sides.

examined at the Equine Hospital of Edinburgh University Veterinary School between 2012 and 2018. The presence of sinus disease was confirmed by the presence of exudate draining from their sino-nasal ostia on standing nasal endoscopy in all cases; the sinoscopic detection of exudate in one or more sinus compartments in all cases and CT imaging (including the presence of fluid/soft tissue attenuation, i.e., from mucosal thickening and/or of accumulated exudate in some sinus compartments in every case).

The CT images were obtained under standing sedation using a Siemens Somaton Volume Zoom 4 slice or a Siemens Definition AS 64-slice (Siemens, Munich, Germany) in a helical scan mode using a 512 × 512 Matrix, 120 Kv, 300 mA, at a slice thickness of 1.5 mm. The images were re-examined by the authors using Horos® (Apple Corporation) software with the axes of the scans adjusted to obtain perpendicular transverse sections of the head for consistent measurements. Bone windows (H70) were used to review the images at a window width (WW) of 4,000 Hounsfield Unit (HU) and window level (WL) of 1,000 (HU).

## Bone Measurements

Linear bone measurements (using the mean of three measurements) were obtained perpendicular to the bone at the following sites.

### Maxillary Bone Thickness at the RMS

Maxillary bone thickness of the RMS wall (**RMB**) was measured at a site level with the midpoint of maxillary Triadan 09 teeth, 2 cm above the dorsal aspect of the facial crest on the affected and contra-lateral sides (**Figure 3A**).

### Maxillary Bone Thickness at the CMS ($N = 2$ Sites)

Maxillary bone thickness of the caudal maxillary sinus (CMS) wall was obtained at two sites; both level with the midpoint of maxillary Triadan 11s in the rostro-caudal plane on the affected and contra-lateral sides.

The ventral measurement (**CMBV**) was made 2 cm above the level of the maxillary crest.

The dorsal measurement (**CMBD**) was made 1 cm above the level of the nasolacrimal duct (**Figure 3B**).

### Frontal Bone Thickness at the Frontal Sinus

Frontal bone (**FB**) thickness was measured at a single site 1 cm dorsal to the junction between the medial aspect of the orbital rim and the caudal aspect of the nasal bone on the affected and contra-lateral sides (**Figure 4**).

### Infraorbital Canal

The maximal infra-orbital canal (IOC) bony wall thickness within the sinuses was obtained at two sites (**IOCB1** and **IOCB2**) level with the midpoint of the Triadan 10s in the rostro-caudal plane, on the affected and contra-lateral sides (**Figure 5A**). The maximum IOC external diameter (**IOCD**) in the CMS was also measured bilaterally. (**Figure 5B**).

### Bony Nasolacrimal Duct

The nasolacrimal duct (NLD) maximal bony wall thickness (**NLDB**) and its maximal external diameter (**NLDD**) were measured caudal to the Triadan 11s on the affected and control sides (**Figures 6A,B**).

Three measurements were made at each of the above sites, when there was evidence of sinus disease (e.g., mucosal thickening or accumulation of exudate) in adjacent sinus compartments. A preliminary examination of the 60 CTs showed involvement of the VCS and/or RMS in every case. However, other than the common presence of low volumes of hypoattenuating fluid in the dependent rostro-ventral aspects of the CMS and dorsal conchal sinuses (DCS) without any generalized mucosal swelling of these compartments (**Figures 3**, **4**, **6–8**) involvement (i.e., mucosal swelling and/or fluid filling) of the more dorsal caudal sinus compartments including DCS and frontal sinus (FS) (conchofrontal sinuses) was present in only 25/60 cases. Consequently, measurements of the more dorsally situated bony structures (frontal bone and the nasolacrimal duct) were not made in the 35 cases without inflammation of

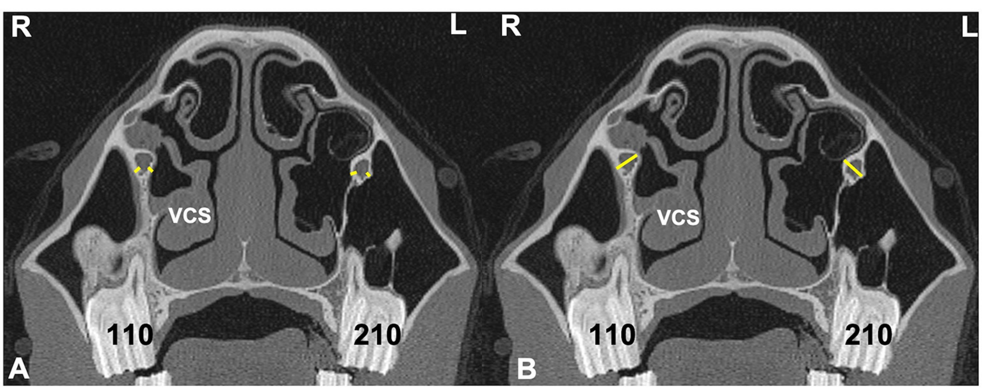


**FIGURE 5 |** Transverse CT images of head of a horse with right-sided sinusitis obtained at the level of Triadan 10s. Some hypoattenuating material is present in the right ventral conchal sinus. **(A)** Sites of two measurements of infraorbital canal (IOC) wall thickness (IOCB 1 and 2) on the affected right (R) and control left (L) sides (yellow lines). **(B)** Sites of measurements of IOC diameter (IOCD) on the affected and control side (yellow lines).

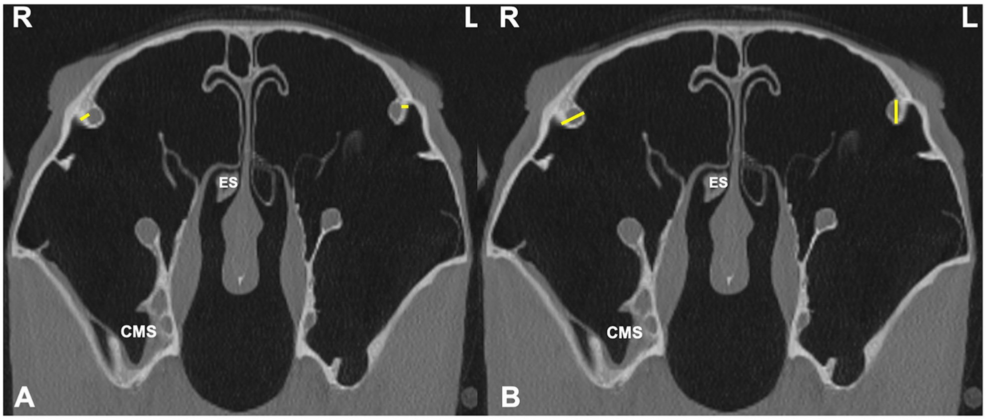


**FIGURE 6 |** Transverse CT images of head of a horse with right-sided sinusitis, obtained at the level of the bony nasolacrimal ducts (NLD), caudal to the Triadan 11s. Small amounts of hypoattenuating material are present within the right caudal maxillary sinus and right ethmoid sinus (ES). **(A)** Measurements sites of the NLD wall bone thickness (NLDB) on the affected (R) and control (L) sides (yellow lines). **(B)** Measurements sites of NLD diameter (NLDD) on the affected (R) and control (L) sides (yellow lines).

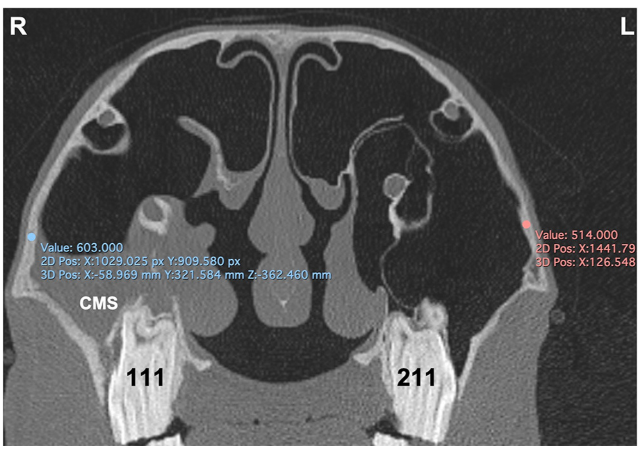


**FIGURE 7 |** Transverse CT image of head of horse with right-sided sinusitis obtained at the level of mid aspect of Triadan 11s. Some hypoattenuating fluid is present within the right CMS. HU measurements of the maxillary bone at the caudal maxillary sinus were obtained 2 cm dorsal the maxillary crest on the affected right (R) and control left (L) sides.

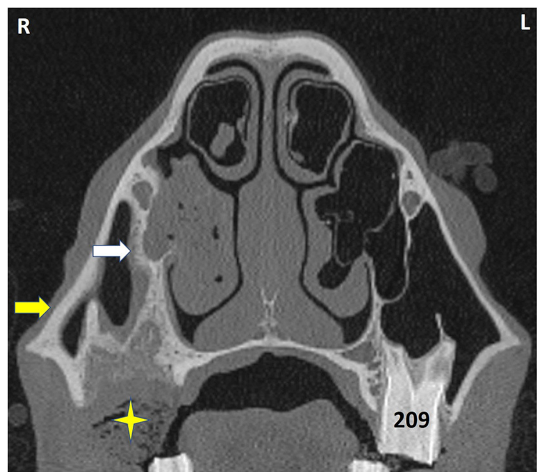


**FIGURE 8 |** Transverse CT of a horse head at the level of Triadan 09. The horse had exodontia of 109 because of dental sinusitis 2 months previously but re-presented with an ipsilateral ventral nasal conchal bulla infection. The VCS contains hypoattenuating material with interspersed gas (shown to be inspissated exudate). The partly-healed post-extraction alveolus contains some food (star) and has grossly thickened and remodeled bone caused by the prior apical infection and exodontia. The bony septum connecting the alveolus and infraorbital canal (white arrow) is much thicker than on the contralateral side, as is its overlying mucosa. The maxillary bone (yellow arrow) is also grossly thickened. L, left; R, right.

these areas, because including these measurements would give erroneous overall findings.

### Bone Density

The density of the maxillary bone assessed in (HU) was measured at the caudal maxillary sinus 2 cm dorsal the maxillary crest at the level of midpoint of Triadan 11s on the affected and control sides (**Figure 7**).

## Repeated CT Examination

Two horses that had clinical resolution of their sinonasal disease had further head CTs performed more than 12 months later for unrelated head disorders and some of the above sinus measurements were repeated.

## Statistical Analyses

The means of the three measurements at each site were calculated. The spread of the mean values for each site subdivided by control and affected were analyzed graphically and using Shapiro–Wilks tests. Measures were compared between control and affected sides using paired $T$-Tests for normally distributed data and using Wilcoxon signed-rank tests. Significance was set as $P < 0.05$. All statistical analyses were performed in RStudio$^{TM}$.

# RESULTS

## Cases

The CT images used in this study were obtained from cases of: dental sinusitis ($n = 45$), subacute primary sinusitis ($n = 3$), chronic (>2 months) primary sinusitis ($n = 8$), small intra-sinus cysts ($n = 2$), mycotic sinusitis ($n = 1$), and oromaxillary fistula ($n = 1$). Only cases with unilateral sinus disease were included to allow use of the contra-lateral sinuses for control measurements. Soft tissue facial swelling was present in 7/60 (11.7%) and epiphora in 4/60 (6.7%) cases.

Many of these images showed grossly recognizable maxillary bone thickening and changes in infra-orbital canal and bony nasolacrimal duct appearance (**Figures 8**, **9**).

Average measures and results of statistical comparisons between control and affected sides are shown in **Table 1**.

The spread of bone thickness and canal diameter measures are shown in **Figure 10**. Bone was significantly thicker in affected than control sides at: RMB ($P < 0.001$), CMBV ($P < 0.001$), CMBD ($P < 0.001$), IOCB1 ($P < 0.001$), IOCB2 ($P < 0.001$), but not at FB ($P = 0.188$) or NLDB ($P = -0.260$). Canal diameters were significantly wider in affected than control sides for: IOCD ($P < 0.001$) and NLDD ($P = 0.002$; **Table 1**, **Figure 10**).

Bone density (HU) did not differ significantly between affected (mean = 1,075, SD = 230.01) and control (mean = 1,100, SD = 200.71) sides [$t_{(58)} = -1.03$, $P = 0.306$].

Two horses that had clinical resolution of their sinonasal disease had further head CTs performed over 12 months later

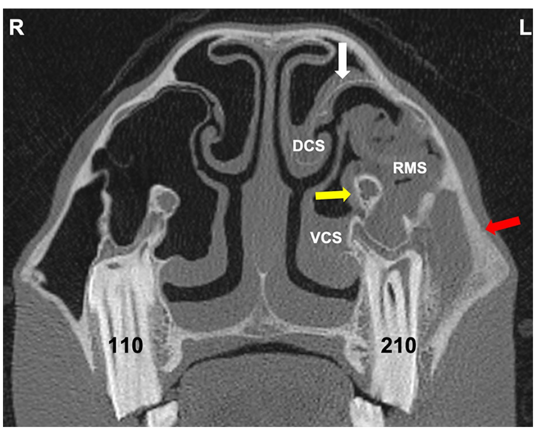


**FIGURE 9 |** Transverse CT image through the rostral sinus compartments at the level of Triadan 10 of a horse with dental sinusitis caused by a Triadan 210 apical infection. The 210 has changes in its buccal root, widened periodontal space, and alveolar bone remodeling. There is resultant empyema of the VCS, DCS, and RMS (with gas bubbles in the latter). There is also thickening of the maxillary septal bulla bone and swollen mucosa on both sides (white arrow), some expansion and wall thickening of the infraorbital canal (yellow arrow) and grossly thickened maxillary bone (red arrow). L, left; R, right.

for unrelated disorders. Bone measurements at four sites in the affected sinuses at the initial visits (mean thickness = 3.0 mm; range = 2.2–3.5 mm) were of reduced thickness (mean 1.9 mm; range = 1.5–1.9 mm) in normal appearing sinuses at their second visit.

# DISCUSSION

This study has shown the presence of osteitis in diseased equine sinuses as manifested by significantly thicker maxillary and infraorbital canal bone thickness, and infraorbital canal and nasolacrimal ducts diameter as compared to the normal contralateral sides. The thickened bones had irregular new bone formation, with evidence of lysis in some areas. This osteitis appears inflammatory in nature with no CT or clinical evidence of bone infection. A CT study of 18 horses with sinus disease by Henninger et al. (9) recorded maxillary bone thickening, endosteal sclerosis, and irregular surfaces in most cases.

Two different CT scanners were used to obtain the images used in this study, including a 4 and a 64 slice unit. Although, the latter can produce higher quality images, this study used the same slice thickness and a bone window for both sets of images and so the results of both units are comparable for the purpose of this study.

The landmarks used for most bone measurement sites were individual cheek teeth. Because these teeth drift mesially (rostrally) with age (23), the measured bone sites, especially the maxillary bone sites would be more rostrally positioned in older horses. However, all maxillary bone measurement sites, both rostrally and caudally located, had very significantly ($p < 0.001$) increased bone thickness and so the possible age-related differences in bone measurement sites would not have affected the results of this study.

Horses with intra-sinus expansive lesions such as sino-nasal cysts or neoplasia usually have large facial swellings (1, 2, 4, 24). Cissell et al. (25) showed that horses with sinonasal neoplasia have osteolysis of adjacent cortical bone along with destructive changes of the nasal conchae, septum, and/or infraorbital canal (25). Unexplained, low-grade, diffuse facial swellings also occur in 24–45% horses with the two most common types of sinus disease, i.e., primary and dental sinusitis (1, 2) (**Figure 1**). The maxillary bone osteitis shown in horses with sinonasal disease in this study can explain these soft tissue facial swelling overlying the maxilla that were clinically present in 7/60 (11.7%) of the current cases. Maxillary osteitis also readily explains the recorded IRU of non-alveolar sinus bones in 60% of horses with primary sinusitis (7). In that study, this non-alveolar IRU lead to false-positive diagnoses of dental sinusitis by blinded observers in 40% of primary sinusitis cases, when focal areas of IRU overlay dental apices (7).

Unilateral epiphora was recorded in 13–34% of horses with primary or dental sinusitis respectively in two previous studies (1, 2). This reported epiphora may have been due to nasolacrimal duct osteitis rather than to pressure from intra-sinus exudate, because the sinuses as noted, are infrequently completely filled with exudate. Although the increased nasolacrimal duct bone

**TABLE 1 |** Difference in measures of bone thickness and canal diameters between control and affected sides.

| Site | Sides compared | Control | | Affected | | Affected > control (%) | Wilcoxon signed rank *Z* statistic | Paired *T*-test *t*-statistic (df) | *P*-value |
|---|---|---|---|---|---|---|---|---|---|
| | | Median (mm) | Mean (SD) (mm) | Median (mm) | Mean (SD) (mm) | | | | |
| RMB | 60 | 2.45 | | 3.39 | | 55 (91.67) | −6.27 | | **<0.001** |
| CMBV | 25 | 2.61 | | 3.05 | | 20 (80.00) | −4.04 | | **<0.001** |
| CMBD | 25 | 3.41 | | 3.78 | | 22 (88.00) | −4.28 | | **<0.001** |
| FB | 19 | | 3.00 (0.73) | | 3.20 (0.67) | 11 (57.89) | | −1.37 (18) | 0.188 |
| IOCB1 | 57 | 1.66 | | 2.35 | | 57 (82.46) | −5.39 | | **<0.001** |
| IOCB2 | 57 | 1.65 | | 1.95 | | 44 (77.19) | −3.92 | | **<0.001** |
| IOCD | 60 | 12.07 | | 14.20 | | 55 (91.67) | −5.97 | | **<0.001** |
| NLDB | 23 | 1.89 | | 2.02 | | 15 (65.22) | −1.13 | | 0.260 |
| NLDD | 23 | | 9.24 (2.24) | | 10.53 (2.39) | 17 (73.91) | | −3.50 (22) | **0.002** |

*RMB, Maxillary bone at rostral maxillary sinus; CMBV, Maxillary bone at ventral site of caudal maxillary sinus; CMBD, Maxillary bone at dorsal site of caudal maxillary sinus; FB, frontal bone thickness; IOCB1, IOCB2, infraorbital canal bone thickness at two sites. IOCD, maximum IOC; NLDB, maximal nasolacrimal duct bone thickness; NLDD, maximum nasolacrimal duct diameter. Bold values indicate P values - standard term.*

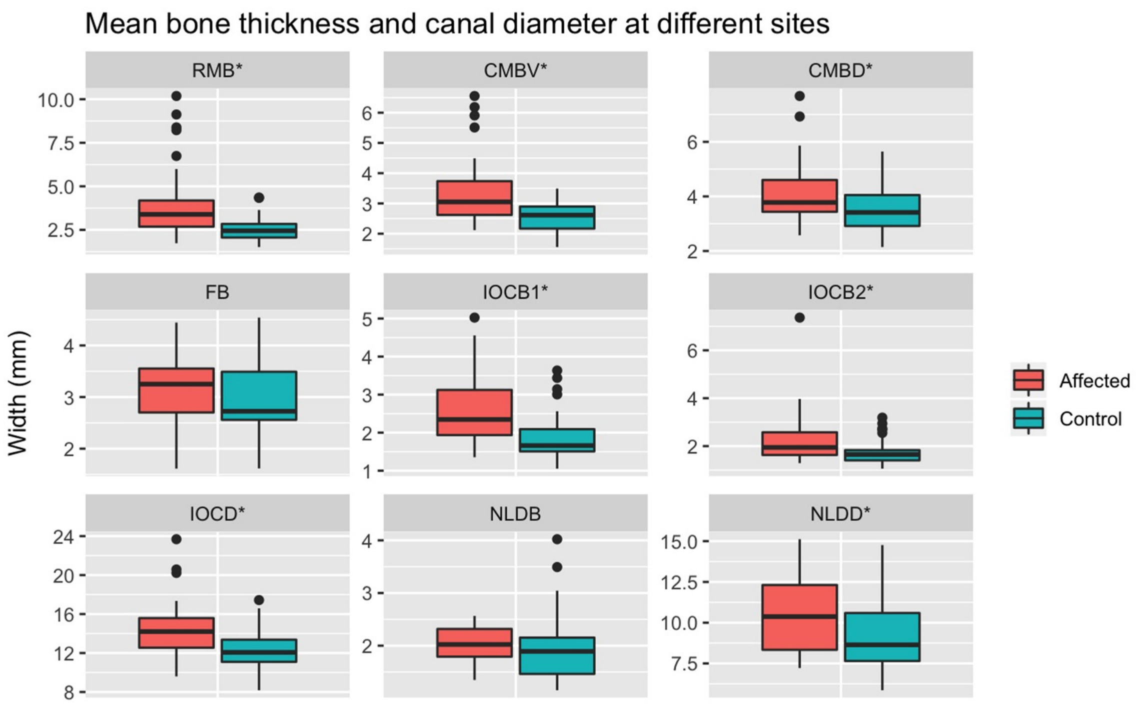


**FIGURE 10 |** Mean measurements at different sites between control and affected sides. RMB, Maxillary bone at rostral maxillary sinus; CMBV, Maxillary bone at ventral site of caudal maxillary sinus; CMBD, Maxillary bone at dorsal site of caudal maxillary sinus; FB, frontal bone thickness; IOCB1, IOBC2, infraorbital canal bone thickness at two sites. IOCD, maximum IOC; NLDB, maximal nasolacrimal duct bone thickness; NLDD, maximum nasolacrimal duct diameter; *significant difference between control and affected sides.

thickness recorded in affected sides in this study was not-significantly different from the control sides, this may have been affected by the smaller number of cases in which this was measurable (23/60 cases had caudal sinus group involvement) and a larger study would be interesting.

Osteitis of the infraorbital canal wall and expansion of the canal diameter were also recorded within affected sinuses. However, there have been minimal clinical reports of trigeminal nerve-related signs such as headshaking or nasal rubbing in horses with sinus disease, that might be expected with such infraorbital canal involvement (1, 2, 9, 15). More recently, Edwards et al. (15) examined the head CTs of 218 horses of which 9% displayed idiopathic headshaking. They found bony infraorbital canal changes including: increased and decreased mineralization, deformity, displacement, and occasionally canal wall disruption in 86% of horses with adjacent disorders (mainly sinusitis). However, infra-orbital canal changes (including decreased mineralization in 29%) were also present in 37% of horses without adjacent disorders (15). The latter finding may indicate that some degree infraorbital canal demineralization is within a range of normality. In any event, these authors only found a weak association between the CT infraorbital canal changes and the presence of idiopathic headshaking.

Sinoscopic fenestration of the MSB can be impeded in some horses with sinonasal disease by the presence of an enlarged infraorbital canal (in addition to MSB sclerosis) (Authors personal observations). The current study confirmed the presence of increased bone thickness and increased diameter of the infraorbital canal in horses with sinus disease, in addition to the mucosal swelling also present on the infraorbital canal (**Figures 3–5**). The MSB bone is thin and irregular, and often barely detectable on radiographic or CT imaging in normal horses. Consequently, its thickness was not measured in this study. However, CT images of equine sinonasal disease show an osteitis-induced increase in MSB bone thickness in some horses, in addition to increased mucosal thickness on both sides (**Figures 2**, **3**). Fenestrating a sclerotic MSB via sinoscopic portals can be difficult or even impossible if marked thickening and calcification of the MSB is present as a result of chronic osteitis, especially if an adjacent enlarged, distorted or displaced infraorbital canal further obstructs safe surgical access. If marked MSB sclerosis and infraorbital canal enlargement or displacement are apparent on CT imaging, surgeons may need to reconsider if that case needs treatment by sinusotomy rather than sinoscopically (authors personal observations).

Effective treatment of horses with sinonasal disease, such as dental extraction or removal of intra-sinus or intra-nasal inspissated exudate results in permanent clinical resolution of the disease in the vast majority of cases (26, 27). Presumably, the sinus-related osteitis also resolves. In two cases where repeat CT imaging was performed there was indication of osteitis resolution, but much larger, structured studies are needed to verify these observations. This apparent resolution of osteitis differs greatly from human chronic rhinosinusitis where many cases are refractory to treatment, with a strong correlation between the degree of sinus osteitis and number of surgical interventions, both features likely reflecting the presence of underlying non-responsive chronic disease, rather than being related to each other. These inflamed bones may even act as reservoirs of pro-inflammatory cytokines that perpetuate sinus inflammation (21).

Despite the increased maxillary bone thickness found in affected cases in this study, bone density did not differ between affected (mean = 1,075 HU) and control (mean = 1,100 HU) sides. This may reflect similar proportions of areas of increased and decreased mineralization in equine sinus osteitis, with both of these changes reported in the infraorbital canals of horses with sinusitis (15).

Histological studies in animal models of human sinus inflammation, (including in some models with induced bacterial sinusitis), and on surgically resected bone from human chronic rhinosinusitis patients show a non-septic sinus bone osteitis, with no evidence of bacterial bone invasion (16–18). Multiple other histological investigations have also shown a low-grade osteitis with new woven bone formation, fibrosis, inflammatory cells, and increased osteoblastic and osteoclastic activity that correspond to the imaging changes, including thickening and irregularity of the sinus walls (17–19, 22). In the absence of any evidence of direct bacterial involvement, this osteitis in human chronic rhinosinusitis patients appears to be stimulated by pro-inflammatory cytokines and other mediators released from the overlying inflamed sinus mucosa (19, 22).

The histology of osteitis in equine sinonasal disease does not appear to have been evaluated to date. However, portions of the MSB are always removed during its fenestration and these could be used in a future histological study on equine sinusitis-related osteitis.

## CONCLUSIONS

Osteitis with thickening of sinus related bones that appears inflammatory in nature was found in most cases of equine sinonasal disease and its presence may lead to soft tissue facial swelling, epiphora, and increased IRU of sinus bones. Recognition of nasolacrimal duct and MSB osteitis, enlargement or distortion is useful in planning the surgical treatment of some cases of sinonasal disease.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

PD designed the study. CP, TL, and DB performed the study execution, RR performed the data analysis. All authors contributed to the data interpretation and manuscript preparation.

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# Computed Tomographic Assessment of Individual Paranasal Sinus Compartment and Nasal Conchal Bulla Involvement in 300 Cases of Equine Sinonasal Disease

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**Background:** Computed tomographic (CT) imaging has allowed new anatomical studies and detailed clinical imaging of the complex, overlapping equine sinonasal structures. Despite the widespread use of CT, no study has specifically identified which compartments are most commonly affected with sinus disorders. CT has also shown the presence of intercurrent, ipsilateral nasal disorders, especially infection of the nasal conchal bullae (NCB) in many cases of sinus disease, but the frequency of intercurrent NCB infections has not been reported.

**Objectives:** To identify which sinus compartments are most commonly affected in horses with clinical sinus disorders and to record the prevalence of NCB involvement in such cases.

**Study Design:** Retrospective examination of CT images of horses with confirmed unilateral sinus disease.

**Methods:** The CT images of 300 horses, from three different equine hospitals with clinically confirmed sinus disease [mainly dental (53%) and primary sinusitis (25.7%)] were retrospectively examined to determine which sinus compartments and NCBs were affected.

**Results:** The rostral, more dependent sinus compartments were most commonly involved, i.e., the rostral maxillary sinus in 284/300 (94.7% affected) and the ventral conchal sinus (87% affected). The caudal maxillary sinus (65.3%), dorsal conchal sinus (52.7%), frontal sinus (26%), ethmoidal sinus (32%) and sphenopalatine sinus (28.7%) were less commonly affected. There was infection or destruction of the ipsilateral NCBs in 56% of horses with sinus disorders, including the ventral NCBs in 42.3%, dorsal NCBs in 29% and both NCBs in 18% of cases.

**Main Limitations:** The horses with sinonasal disease that underwent head CT imaging include more problematic cases and horses of high value, rather than the general horse population.

**Conclusions:** The more dependant (i.e., the RMS and VCS) sinus compartments are most commonly involved in sinus disorders, with the RMS involved in nearly every case. The more dorsally located sinuses (i.e., caudal group) are less commonly involved. Many horses with sinus disease also have disorders of their nasal conchal bullae and so the term *sinonasal disease* seems appropriate for these disorders.

**Keywords: equine, equine sinonasal imaging, equine sinus disease, equine nasal conchal bulla disease, sinus compartment involvement**

## INTRODUCTION

Sinus disorders are important diseases in horses due to their frequent refractory nature. They can have multiple causes including cheek teeth apical infection, benign and malignant space-occupying intra-sinus growths, trauma, oro-maxillary fistulae and mycotic infections (1–8). In the absence of any identifiable underlying cause for sinus disorder, the remainder by default, are termed primary sinusitis (1, 2). Radiography can provide a limited amount of diagnostic information for these cases due to the complexity of the overlapping sinonasal structures that additionally, become distorted when diseased (9). The use of computed tomography (CT) has had a major impact on the diagnosis of equine sinonasal disorders, allowing detailed imaging of these complex anatomical structures in multiple planes without the presence of overlapping structures (10–16). In particular CT imaging has allowed accurate identification of cheek teeth periodontal, apical and endodontic disease (12, 15, 17–19).

The use of CT has also allowed three-dimensional anatomical studies to be performed that have significantly changed our understanding of sino-nasal and dental anatomy (20–24). In addition to helping diagnose the causes of sinus diseases and identify which compartments are involved, to allow more targeted surgical treatment, CT imaging has also clearly shown the presence of concurrent nasal disorders in many horses with sinus disorders (11, 25, 26). These include the presence of ipsilateral NCB infections in addition to nasal mucosal swelling and the presence of intranasal sequestrae, inspissated exudate, and sino-nasal fistulae (11, 25–27), some of which can be seen on nasal endoscopy (3–5, 26). The recent identification of ongoing nasal disorders including NCB empyema explains why some horses with sinus disorders do not respond to apparently effective treatment of the sinus disorder (5, 25, 26).

CT imaging can readily identify NCBs that are filled with fluid attenuating material, with or without regions of hypoattenuation (indicative of liquid and inspissated exudate) (**Figures 1**, **2**). In other horses CT has identified gross disruption or even absence of the ipsilateral NCBs usually with distortion or local loss of the adjacent nasal concha (**Figure 3**). These changes appear to be advanced stages of NCB infection with their destruction or loss, along with local nasal conchal damage. Endoscopy of some such cases shows the presence of intranasal inspissated exudate and thin conchal sequestra at the caudal aspect of the middle meatus (**Figure 4**). However, it remains possible that absent or distorted NCBs and local nasal conchal distortion without the presence of exudate, could be developmental abnormalities or due to disorders other than ipsilateral sinus disease. That being the case, these changes should be bilaterally present in the nasal cavities in equal proportions.

Despite the importance of equine sinonasal disease, very limited information is available on which sinus compartments are most commonly involved in sinusitis. A study of 200 sinus disease cases where compartment involvement was determined by radiography and surgical exploration found the caudal maxillary (CMS), RMS and VCS compartments to be most commonly involved (3). In contrast, a recent CT study of 28 horses with sinus disorders found the RMS to be the most commonly involved compartment (was involved in all horses). No large study has objectively documented which sinus compartments are most commonly involved in disease.

The aim of this study was to retrospectively examine CT images from horses with sinoscopically and surgically confirmed unilateral sinus disease to identify which sinus compartments were affected and also to examine how many of these cases had empyema, destruction or loss of the ipsilateral NCBs. The causes of equine sinus disorders vary between different studies (1–8), likely due to different caseloads in different clinics and different geographical areas. In order to obtain more representative results in the current study, the retrospective examinations were performed using cases from three different clinics.

## MATERIALS AND METHODS

The studies were performed in three clinics with different caseloads in different areas of the UK, including the Equine Hospitals of The Royal (Dick) School of Veterinary Studies (RDSVS), Edinburgh and of the Royal Veterinary College (RVC), London and Rossdales Equine Hospital (Rossdales), Newmarket. In each clinic, the CT images (all performed under standing sedation) and the clinical records of 100 recent, consecutive cases of clinically confirmed unilateral sinus disease were retrieved and re-examined by one author from each institution. Re-examination of these CT images were specifically performed to detect NCB and sinus compartment involvement using the pre-agreed criteria described later. A consensus was reached on images with ambivalent findings.

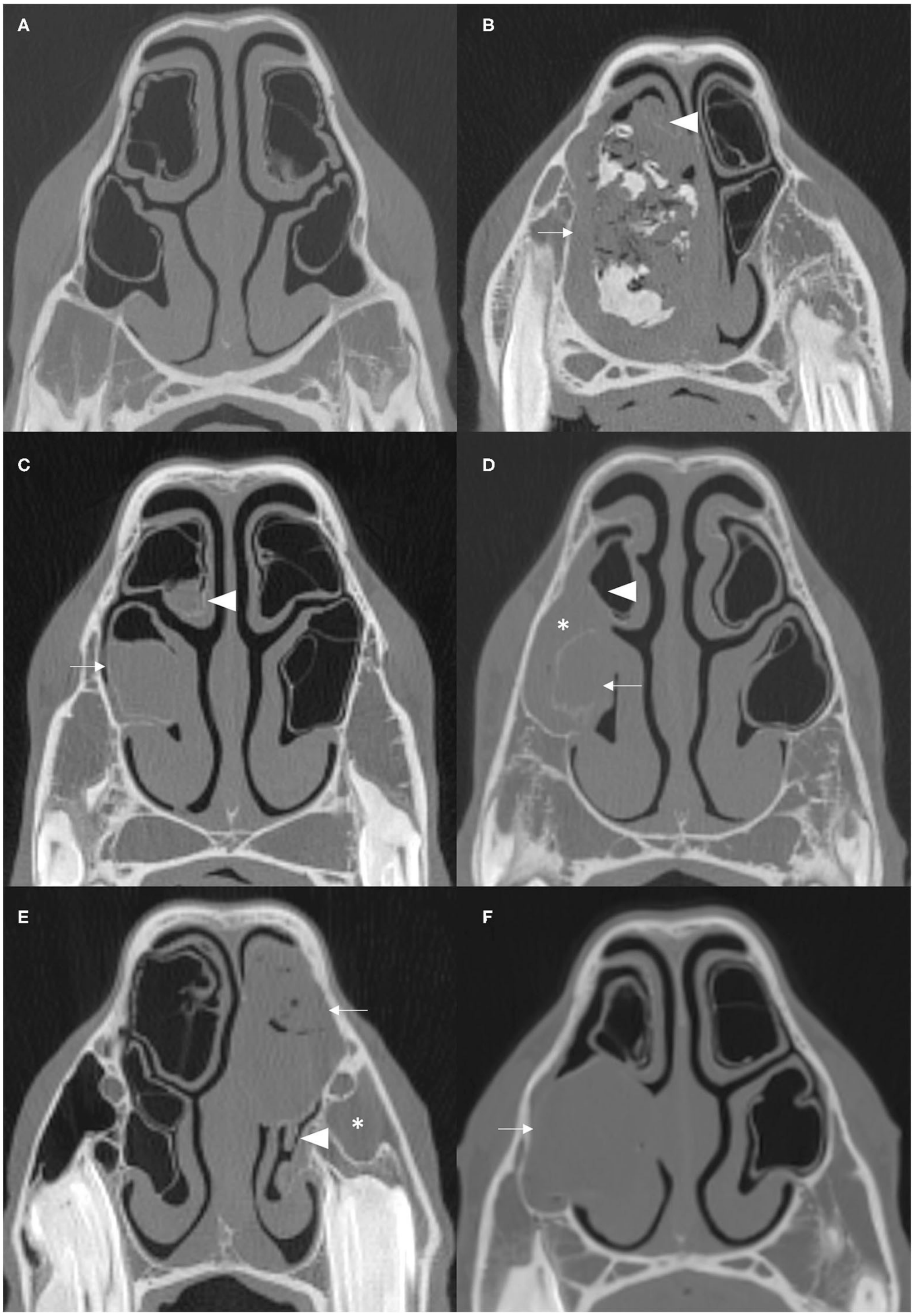


**FIGURE 1 |** Transverse CT images of normal NCBs and of various types of NCB empyema. **(A)** Normal NCBs. **(B)** Mixed hyper- and hypoattenuation within a distended VCB, representing mineralisation and gas, respectively, within soft tissue attenuating material (arrow). There is compression and severe damage of the ipsilateral DCB (arrowhead) (mineralised nasal conchae found on histology—disorder of 10 years clinical duration). **(C)** Soft tissue/fluid attenuating material fills most of VCB (arrow) and the ventral aspect of DCB (arrowhead). **(D)** Soft tissue/fluid attenuating material fills the entire VCB (arrow), which has a thickening of the bony concha and has surrounding soft tissue/fluid attenuating material flowing from the ipsilateral sinuses (asterisk) and mild damage to the ipsilateral DCB (arrowhead). **(E)** The DCB is partially filled with material of mixed soft tissue and gas attenuation, reflecting inspissated purulent exudate (arrow). There is moderate damage of the ipsilateral VCB (arrowhead) and ipsilateral sinus empyema (asterisk). **(F)** The VCB is distended with homogenous soft tissue/fluid attenuating material (arrow). All CT images were reconstructed using using a bone filter (Window Level 800 HU, Window Width 2,800 HU). The right side of the patient is on the left side of the image. The transverse images **(A–C)** are at the level of the Triadan 08 maxillary cheek teeth, **(D,F)** at the level of the Triadan 07s and **(E)** is level with the distal (caudal) aspect of Triadan 08s.

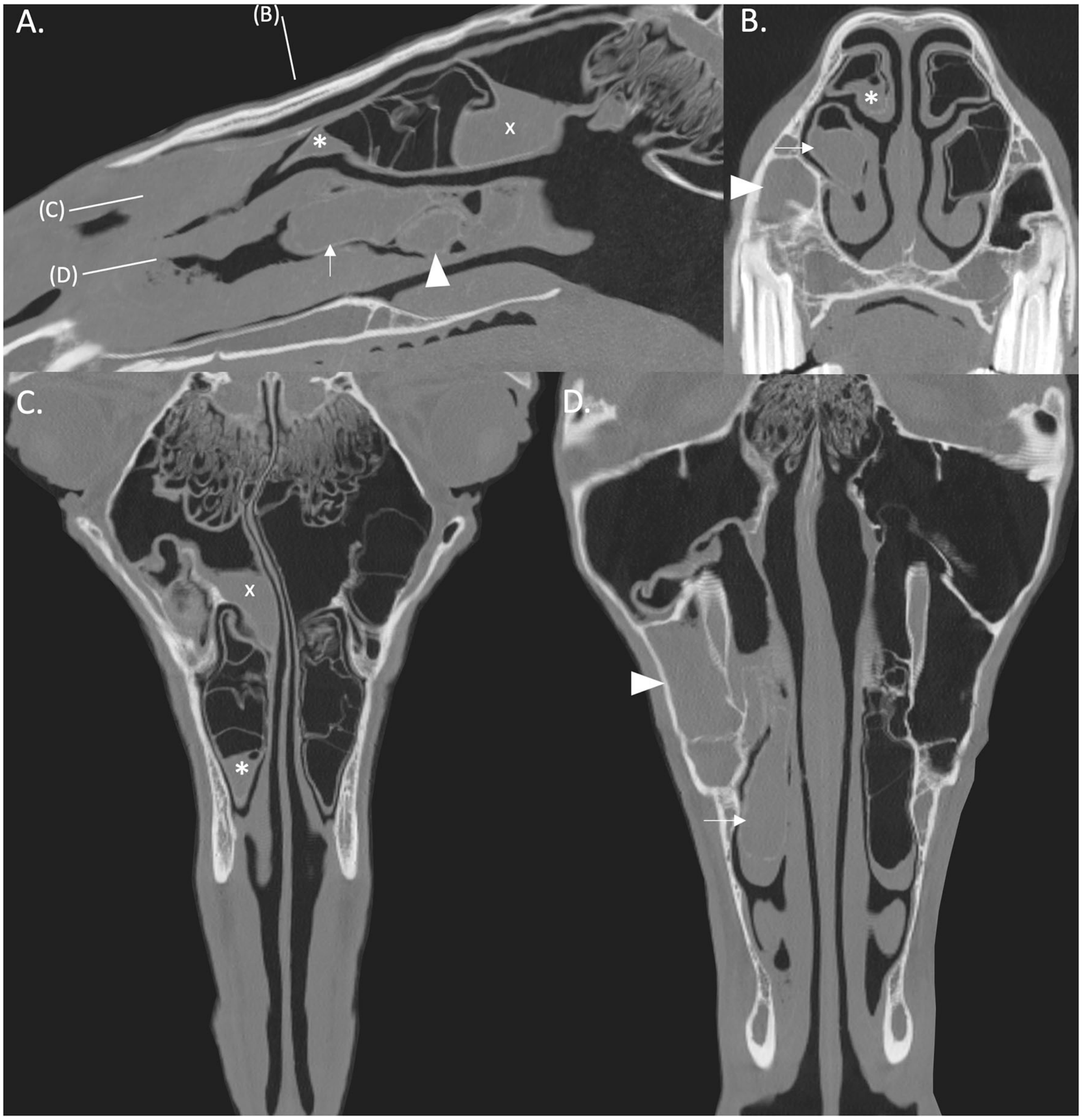


**FIGURE 2 | (A)** Right parasagittal CT reconstruction with lines representing the locations of images (B–D). **(B)** Transverse CT image. **(C,D)** Dorsal CT reconstruction at the level of the DCB and VCB, respectively, the rostral aspect is toward the bottom of the image. There is empyema of the VCB (arrow) with ipsilateral sinusitis of the rostral (arrowhead) and caudal (x) paranasal sinus compartments. There is thickening of the mucosa of the rostral aspect of the right DCB (asterisk). All CT images are displayed using a bone filter (Window Level 800 HU, Window Width 2,800 HU). The right side of the patient is on the left side of the image.

## Cause of Sinusitis

The etiology of each case of sinus disease as determined by their initial CT imaging, clinical, nasal endoscopic and sinoscopic examinations, surgical findings and by response to treatment was obtained from the clinical records. These included subacute (<2 months duration) and chronic (>2 months duration) primary sinusitis; dental sinusitis, sinus cysts; mycotic sinusitis; intra-sinus progressive ethmoid haematoma (PEH), sinus trauma; oro-maxillary fistula and sinus neoplasia and are presented in **Table 1**.

## CT Imaging

At the R(D)SVS, head CT images were obtained using a Siemens Somaton Volume Zoom 4 slice or a Siemens Definition AS 64-slice (Siemens, Munich, Germany) in a helical scan mode using a 512 × 512 Matrix, 120 Kv, 300 mA, at a slice thickness of 1.5 mm.

At the RVC, head CT images were obtained using a 16-slice multi-detector CT scanner (GE Lightspeed Pro 16, GE Medical Systems, Berkshire, UK) using 120 kV, 200 mAs, 1.25 mm slice thickness with an inter-slice interval of 1.25 mm. Images were

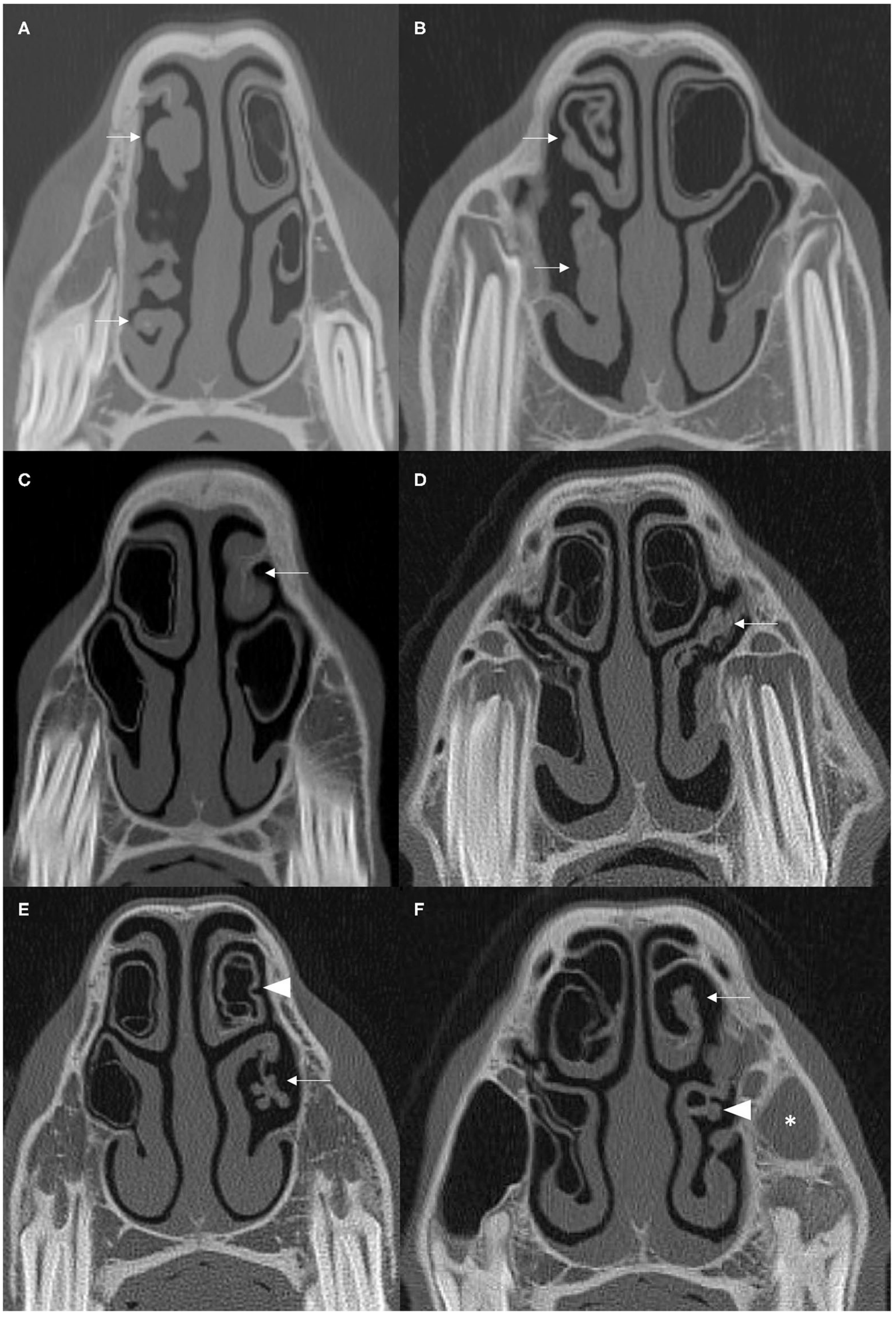


**FIGURE 3 | (A,B)** Transverse CT images of two cases with moderate to severe damage of ipsilateral DCBs and VCBs (arrows) with distortion of the adjacent nasal concha. **(C)** The left DCB is not present (arrow) and there is contraction and thickening of the remaining adjacent nasal concha. **(D)** There is loss of the left VCB (arrow) with flattening and irregular thickening of the surrounding ventral nasal concha. **(E)** There is loss of the left VCB (arrow) with distortion and atrophy of the lateral aspect of the surrounding ventral concha. The walls of the ipsilateral DCB is hyper-attenuated and has a scalloped appearance (arrowhead). **(F)** There is loss of the DCB (arrow) and distortion and thickening of the adjacent concha and loss of identifiable structure in the VCB (arrowhead). There is soft tissue/fluid attenuation filling the left rostral maxillary sinus consistent with ipsilateral sinusitis (asterisk). All CT images are displayed using a bone filter (Window Level 800 HU, Window Width 2,800 HU). The right side of the patient is on the left side of the image. Transverse images **(A,E)** are at the level of the Triadan 07 maxillary cheek teeth, **(B–D)** at the level of the Triadan 08s and **(F)** is level with the distal (caudal) aspect of the Triadan 08s.

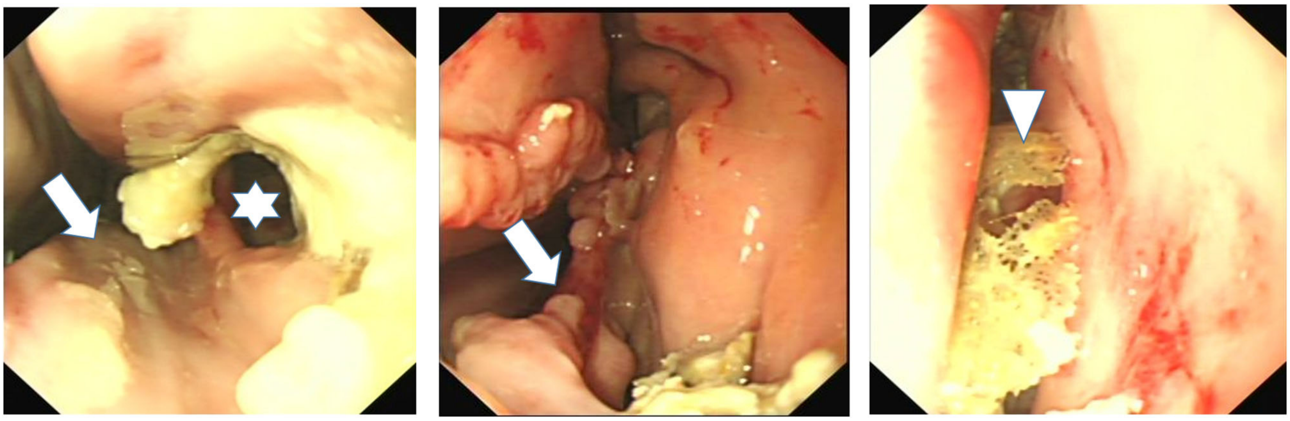

**FIGURE 4 |** Nasal endoscopy image of the caudal aspect of the middle meatus of horses with ipsilateral sinus and nasal conchal bulla disease. Left image shows loss of VCB and of caudal aspect of ventral concha (arrow) and a fistula into VCS (star) surrounded by inspissated exudate. Middle image also shows loss of VCB and distortion of adjacent ventral concha with inspissated exudate at VCB site. The right image shows sequestered conchal bone lying in middle meatus after VCB infection and sequestration of its bony wall.

**TABLE 1 |** Cause of sinus disease in 100 horses at each of three different centers.

| Cause of Sinusitis | RDSVS | RVC | Rossdales | Combined |
|---|---|---|---|---|
| Subacute primary sinusitis | 4% | 14% | 14% | 10.7% |
| Chronic primary sinusitis | 20% | 10% | 15% | 15% |
| Dental Sinusitis | 63% | 49% | 47% | 53% |
| Sinus Cyst | 8% | 10% | 7% | 8.3% |
| Mycotic sinusitis | 3% | 3% | 0% | 2% |
| Progressive ethmoid haematoma | 0% | 1% | 2% | 1% |
| Traumatic Sinusitis | 1% | 6% | 2% | 3% |
| Oro-maxillary fistula | 1% | 5% | 0% | 2% |
| Sinus neoplasia | 0% | 2% | 12% | 4.7% |

*RDSVS, University of Edinburgh; RVC, University of London.*

reconstructed using both a bone and soft tissue algorithm in a 512 × 512 matrix.

At Rossdales, head CT images were obtained using a 16-slice multi-detector CT scanner (GE Lightspeed Pro 16, GE Medical Systems, Berkshire, UK) using 120 kV, 200 mAs, 0.625 mm slice thickness. Images were reconstructed using both a bone and soft tissue algorithm in a 512 × 512 matrix.

At all institutions the images were re-examined by the authors using Horos™ (Horos Project) software with the axes of the scans adjusted to obtain perpendicular transverse sections of the head for consistent measurements. Bone windows were used to review the images at a window width (WW) of 4000 Hounsfield Unit (HU) and window level (WL) of 1000 (HU).

## Individual Sinus Compartment Examinations

The CT images were examined for the presence of inflammation of individual sinus compartments as adjudged by the presence of fluid/soft tissue attenuation, i.e., from mucosal thickening and/or of accumulated exudate in their lumina. The conjoined dorsal conchal sinus (DCS) and the frontal sinus (FS) are usually considered as the single conchofrontal sinus (CFS) compartment. However, because long-term observations of clinical cases showed an apparent disparity between the involvements of the DCS and FS in sinus disease, inflammation of these compartments were recorded separately in this study. Frequency of individual sinus compartment involvement were compared between cases with dental and non-dental sinusitis using Chi-Squared tests in RStudio™, significance was set at $P < 0.05$.

## NCB Examinations

All cases were examined for alterations of the ipsilateral dorsal and ventral NCBs. NCBs with fluid or fluid and gas attenuation were readily identified as "NCB empyema" (**Figures 1**, **2**). Other NCB changes including their deformation or absence, usually with various deformations of the adjacent ventral or dorsal nasal conchae (**Figure 3**) were also recorded as "NCB damage." In case some of these absent or distorted NCBs and distorted adjacent nasal concha were developmental, or otherwise not related to concurrent ipsilateral sinus disease, all contralateral nasal cavities were also similarly examined for NCB changes.

It had been noted that the caudal aspects of NCBs adjacent to infected VCS and RMS compartments sometimes showed slight localized swelling of their walls, but the bullae did not contain any fluid attenuating material and were of normal appearance otherwise (**Figure 5**). These NCBs were classified as being normal. The NCBs adjacent to erupting cheek teeth in some young horses were compressed in a medial direction (23) and these changes were also regarded as a normal feature.

# RESULTS

## Cause of the Sinus Disease

The causes of sinus disease in the 100 horses at the three centers and the combined values are presented in **Table 1**.

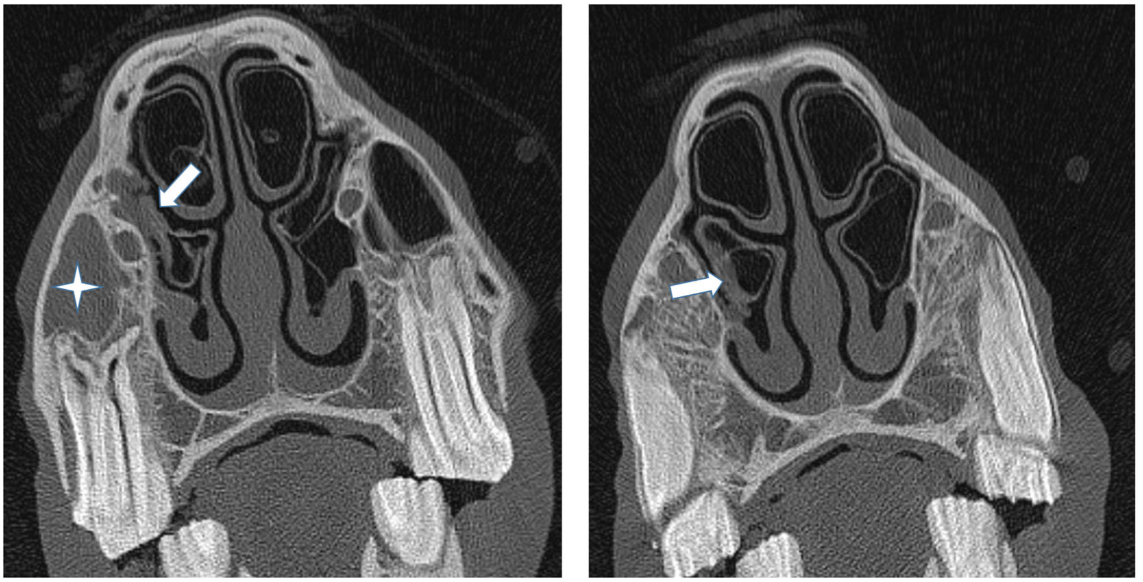

**FIGURE 5 |** (Left) Transverse CT images of a horse suffering from empyema of the right RMS (star). The caudal aspect of the adjacent ventral concha is thickened and irregular (arrow) but more rostral sections (Right) showed the VCB not to contain exudate and it was classified as being normal.

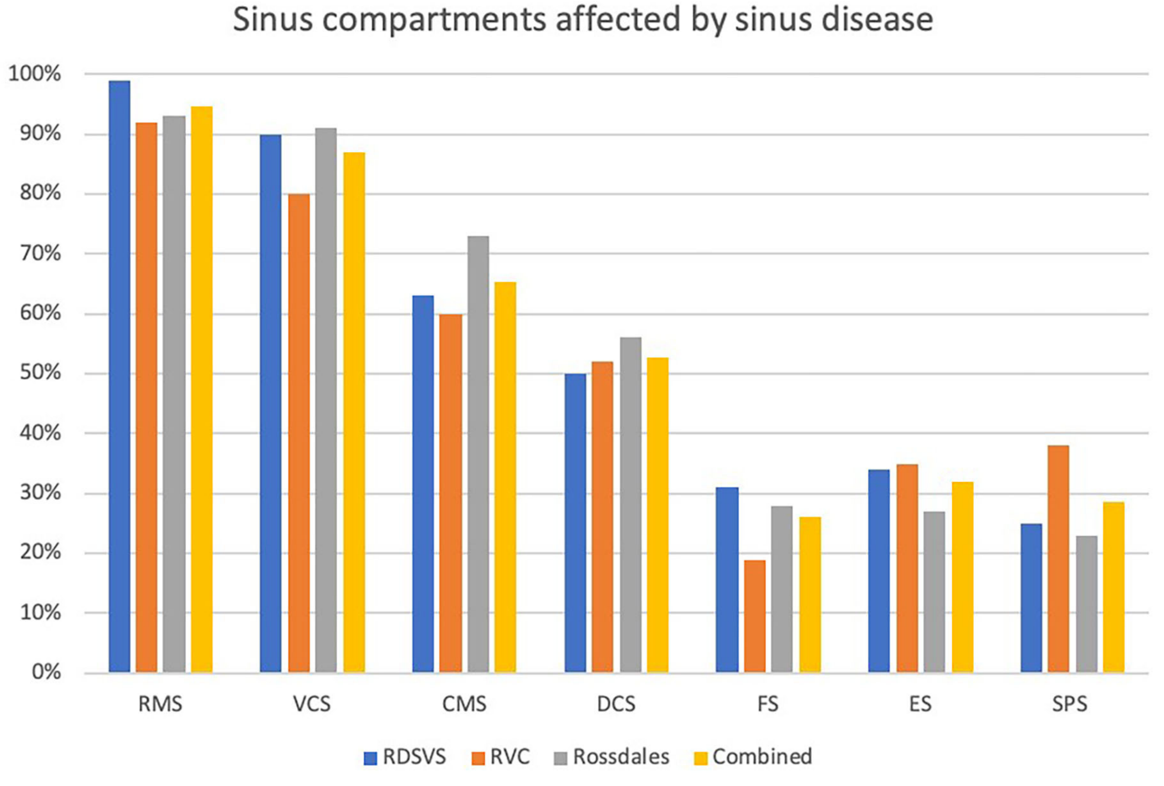


**FIGURE 6 |** Histogram showing proportions of the different sinus compartments that were affected in 100 horses with sinus disease at each of three different centers. RMS, rostral maxillary sinus; VCS, ventral conchal sinus; CMS, caudal maxillary sinus; DCS, dorsal conchal sinus; FS, frontal sinus; ES, ethmoidal sinus (also termed the middle conchal sinus); SPS, sphenopalatine sinus (RDSVS, University of Edinburgh; RVC, University of London).

**TABLE 2 |** Proportions of the different sinus compartments that were affected in 100 horses with sinus disease at each of three different centers.

| Compartment affected | Combined $N = 300$ | Dental sinusitis $N = 160$ | Non-dental sinusitis $N = 140$ | $X^2$ Dental vs. Non-Dental |
|---|---|---|---|---|
| RMS | 284 (94.7%) | 157 (98.2%) | 127 (90.7%) | $X^2$ (1) = 6.72 **$P = 0.009$** |
| VCS | 261 (87%) | 140 (87.5%) | 121 (86.4%) | $X^2$ (1) = 0.01 $P = 0.918$ |
| CMS | 196 (65.3%) | 96 (60%) | 100 (71.4%) | $X^2$ (1) = 3.82 $P = 0.051$ |
| DCS | 158 (52.7%) | 75 (46.9%) | 83 (59.3%) | $X^2$ (1) = 4.13 **$P = 0.042$** |
| FS | 78 (26%) | 35 (21.9%) | 43 (30.7%) | $X^2$ (1) = 2.59 $P = 0.108$ |
| ES | 96 (32%) | 44 (27.5%) | 52 (37.1%) | $X^2$ (1) = 2.76 $P = 0.096$ |
| SPS | 86 (28.7%) | 29 (18.1%) | 57 (40.7%) | $X^2$ (1) = 17.54 **$P < 0.001$** |

*$X^2$, Chi-square test with "Yates continuity correction," significant P-values in bold; RMS, rostral maxillary sinus; VCS, ventral conchal sinus; CMS caudal maxillary sinus; DCS, dorsal conchal sinus; FS, frontal sinus; ES, ethmoidal sinus (also termed the middle conchal sinus); SPS, sphenopalatine sinus.*

## Individual Sinus Compartment Involvement

The proportions of individual sinus compartments affected by disease in each equine center are shown in **Figure 6** and **Table 2**. There was a significantly higher frequency of RMS involvement in the Dental (98.2%) than the Non-dental (90.7%) sinusitis group [$X^2$ (1) = 6.72, $P = 0.009$]; and significantly lower DCS and SPS involvement in the Dental (46.9 and 18.1%, respectively) than the Non-Dental (59.3 and 40.7%, respectively) sinusitis group [DCS $X^2$ (1) = 4.13, $P = 0.042$ and SPS $X^2$ (1) = 17.54, $P < 0.001$]. The frequency of other sinus compartment involvement did not differ significantly between the groups.

## Changes to Ipsilateral and Contralateral NCBs

The proportions of ipsilateral NCBs with empyema or "loss/damage" in each center are listed in **Table 3**. A consensus was reached on three ambivalent cases of possible NCB damage. Examination of the contralateral nasal cavity showed the presence of fluid attenuating material in DCBs ($n = 4$) (**Figure 7**) and VCBs ($n = 2$) and of loss or damage to VCBs ($n = 2$) and DCBs ($n = 2$), i.e., overall, 10/300 (3.3%) contralateral NCBs had abnormalities, including 6/300 (2%) with empyema. One horse suffering from a sinus cyst was found to have a fluid attenuating material in the region of its contralateral DCB that was later histologically shown to be a nasal cyst. Two horses had nasal abscesses adjacent to, but not involving their NCBs and these cases were classified as having normal NCBs.

# DISCUSSION

## Cause of the Sinus Disease

The causes of sinus disease found in this study included 53% dental sinusitis, 26% primary sinusitis; 8% sinus cyst with overall lower (<5%) proportions of mycotic sinusitis, PEH, trauma oromaxillary fistula and neoplasia (**Table 1**). The current findings are similar to a recent clinical audit of sinus disease, that found 45% of cases to be dental sinusitis, 36% primary sinusitis and 7% cysts (RJM Reardon Personal observations) but differ from an earlier clinical study at the same clinic that found primary sinusitis to be most commonly diagnosed cause of sinusitis (45% of cases), along with 20% dental sinusits and 13% sinus cyst (3). These changes in the pattern of sinus disease etiology may reflect changing referral clinic caseloads with higher proportion of primary sinusitis cases currently being treated in general practice, and with the more difficult, non-responsive cases, such as horses with dental sinusitis being referred. Additionally, not all cases of equine sinonasal disease receive CT imaging. Instead, the more complex and chronic

**TABLE 3 |** Proportions of 100 horses at each of three clinics with unilateral sinus disease that also had changes to their ipsilateral nasal conchal bullae (NCB) including their ventral conchal bullae (VCB) and dorsal conchal bullae (DCB).

| NCB involvement | RDSVS | RVC | Rossdales | Combined |
|---|---|---|---|---|
| VCB empyema | 24% | 14% | 22% | 20% |
| VCB damaged | 26% | 24% | 17% | 22.3% |
| DCB empyema | 15% | 6% | 23% | 14.7% |
| DCB damaged | 17% | 16% | 12% | 14.3% |
| NCB involvement | 58% | 54% | 56% | 56% |
| No NCB involvement | 42% | 46% | 44% | 44% |
| Both NCB involved | 24% | 6% | 18% | 16% |

*RDSVS, University of Edinburgh; RVC, University of London.*

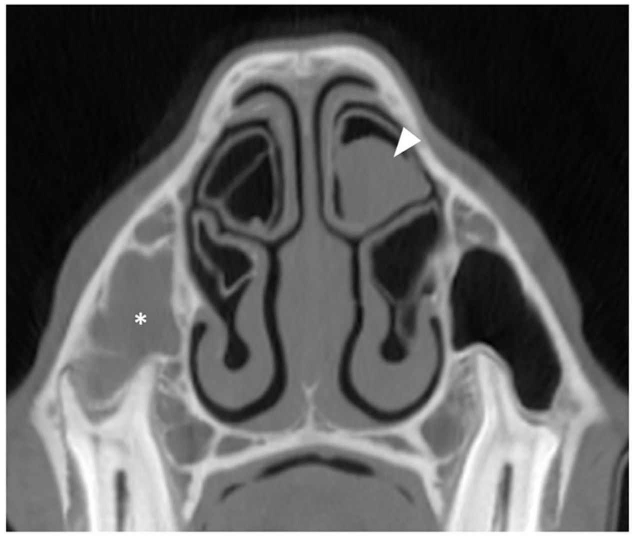

**FIGURE 7 |** Transverse CT image of a horse suffering from right-sided sinus disease showing empyema of the right RMS (asterisk). The contralateral DCB contains soft tissue/fluid attenuating material indicative of empyema (arrowhead). All CT images are displayed using a bone filter (Window Level 800 HU, Window Width 2,800 HU). The right side of the patient is on the left side of the image.

cases and the more valuable horses are more likely to have such imaging and so the current findings may be biased in this respect.

## Sinus Compartment Involvement

This study found the two rostral compartments, i.e., the RMS (94.7% affected) and VCS (87%) to be most commonly affected compartments in all 300 horses with sinus disease (**Table 2**; **Figure 6**). There was decreasing involvement of the other compartments in a caudo-dorsal direction, from 65% involvment of the CMS to 28.7% of the SPS (**Table 2**; **Figure 6**). The Triadan 09s are the cheek teeth most commonly involved in dental sinusitis (1, 3, 4) and dental sinusitis was the most common cause of sinusitis in this study leading to empyema of the two rostral compartments with 98.2% RMS and 87.5% VCS involvement in cases of dental sinusitis. However, the RMS and VCS were affected in 90.7 and 86.4%, respectively, of non-dental sinusitis cases. The RMS and VCS are the most anatomically dependant compartments when the horse's head is in the resting or grazing positions and it is easy to understand how exudate would accumlate in them. Due to their dependant position all intra-sinus fluids, including normal mucus secretions as well as exudates have to be fully cleared by mucociliary clearance without the gravity assistance that occurs in the more dorsal sinus compartments. It is not surprising therefore that with sinus disease, some of this poorly draining exudate in the CMS and VCS later dehydrates and becomes inpissated (3, 4) leading to chronic or even permanent sinus disease.

The other caudal group of compartments, especially the three most dorsal compartments, i.e., the ES, FS and SPS are less dependant and were least commonly affected, but with higher involvement (non-significantly in 3/5 compartments) in non-dental sinusitis. These findings are somewhat similar to a CT study of 28 horses with sinus disease that found RMS involvement in 28/28 cases; CMS in 24/28; VCS and CFS in 23/28 and SPS in 18/28 (24). However, the current results differ from a study of 200 horses with sinus disorders, where CT imaging was not performed and where sinus compartment involvement was largely determined during surgical and sinoscopic exploration (3). In that study, the CMS (78% involvement) and RMS (61%) were most commonly affected, with lower involvement of the VCS (54%), CFS (48%) and combined ES and SPS (7%) (3). The difference between the current and that clinical study could be explained by inter-compartmental movement of blood and exudate during surgical exploration of the affected sinuses in the latter study (3), especially as some sinus osteotomies were performed in recumbent horses under general anesthesia.

There is no doubt that standing CT imaging is highly accurate and is the gold standard technique to identify sinus compartment involvement in cases of sinus disease. Consequently, the results of the current study are more accurate than clinical studies. This study again emphasizes the great importance of the two small, rostral VCS and RMS compartments in sinus disease and again highlights the enormous value of CT imaging in detecting sinus compartemnt involvement.

## Intercurrent Nasal Disorders

The equine nasal cavity is difficult to examine clinically and unless the middle meatus is carefully endoscopically examined (with a narrow endoscope, ideally $<10$ mm diameter), nasal endoscopy may not reveal much information. Partly for these reasons, equine nasal disease has been a neglected clinical area until recently. The use of CT has recently allowed new anatomical studies of this area, especially of the hitherto poorly described NCBs (24, 25), that in turn has allowed these structures now to be more clearly radiographically imaged (28). Most significantly, CT imaging has been proven invaluable in identifying intercurrent nasal disorders in horses with sinus disease, especially the presence of NCB infections (11, 24–26) and also sino-nasal fistulae (26).

The presence of infected NCB has been shown to be the cause of continuing clinical signs (unilateral purulent nasal discharge) in apparent non-responsive cases of sinus disease. Rarely NCB infections can cause chronic unilateral nasal discharge in the absence of ipsilateral sinus disease (25). Additionally, the recognition of this disorder has drawn clinical attention to this area and allowed nasal abnormalities other than infected NCBs including inspissated exudate, conchal sequestrae, mycotic plaques and sino-nasal fistulae to be identified on imaging and endoscopically (PM Dixon, unpublished observations).

No previous study appears to have reported the prevalence of ipsilateral NCB infection in horses with sinus disease. This study has shown 56% of horses with sinus disease to have changes in their ipsilateral NCBs, including NCB empyema in 34.7%, destructive changes with loss of the NCB and adjacent nasal conchal changes in 36.6% (16% of horses had one ipsilateral bulla with empyema and the other with destructive changes) (**Table 3**). NCB destructive changes are assumed to be caused by abscessation followed by rupture of these bullae. Nasal endoscopy has sometimes shown thin fragments of lace-like conchal bones that are possibly decalcified by chronic infection (not readily detectable on CT imaging) along with inspissated exudate adjacent to the NCB sites (RJM Reardon personal observations).

The pathogenesis of concurrent ipsilateral NCB infection in horses with sinus disease is likely to include their contamination by infectious exudate flowing from the adjacent sino-nasal drainage ostia, which can directly flow over the more commonly affected VCB. Additionally, horses with sinus disease invariably have swollen nasal mucosa (11) that could also disrupt normal NCB drainage and predispose to their infection. In horses with a sinonasal fistula (that are usually from the rostral aspect of the VCS into the middle meatus), it is very possible that the thin wall between the VCS and VCB could also be damaged leading to VCB empyema.

It was considered possible that the observed damaged or absent NCBs were not caused by the adjacent sinus disease but instead were a developmental abnormality or caused by some other non-sinus related mechanism such as mycotic rhinitis. Consequently, examination of the contralateral NCBs was performed in all cases. Surprisingly it showed 6/300 horses (2%) to have empyema of the contralateral NCBs that had not been clinically observed with only 4/300 cases (1.3%) having destructive changes. These findings suggest that the damaged or absent NCBs on the ipsilateral side to the sinus disease, that were in present in 110/300 (36.6%) of horses (27.5 times more commonly than on the contralateral side), were a sequel to the ipsilateral sinus disease.

The great clinical importance of intercurrent nasal disease in horses with sinus disorders is now well recognized and are currently treated appropriately, such as by draining NCBs and transendoscopic removal of sequestrae and inspissated exudate. Nevertheless, many long-term previous studies of sinus disease have shown that the majority of cases treated prior to the recognition of intercurrent nasal disease did resolve fully (8, 29, 30). However, this may because the treatments in these earlier studies usually involved sinusotomy and nasal fistulation, that along with prolonged high-volume sinus lavage, likely dislodged inspissated exudate and sequestrae from the NCB and middle meatus as well as from the sinuses, thus unknowingly treating any intercurrent nasal disorders. The finding that some horses have absence of some NCBs and distortion of adjacent nasal concha without any local exudate suggests that following infection and destruction of NCBs, with complete loss of NCB sequestra and inspissated exudate, that the clinical signs of NCB infection will also fully resolve.

## CONCLUSIONS

This multicenter CT study has shown dental sinusitis, primary sinusitis and sinus cysts to be the most common causes of equine sinus disease. The two rostral compartments, especially the RMS, are affected in nearly every case of sinus disease, with the CMS, CFS and other more dorsal compartments less commonly affected. The ipsilateral NCBs show evidence of current or past infection in 56% of horses with sinus disease. Increased attention should be given by imagers and clinicians to the high prevalence of intercurrent nasal disease in horses with sinus disorders.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

PD contributed to study design and execution, data analysis and interpretation, and manuscript preparation. RM contributed to study execution, interpretation, and manuscript preparation. TB contributed to study execution, data analysis, and manuscript preparation. RR contributed to study design, data analysis and interpretation, and manuscript preparation. All authors contributed to the article and approved the submitted version.

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# Occlusal Fissures in Equine Cheek Teeth: A Prospective Longitudinal *in vivo* Study

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**Background:** It has been suggested that fissures of the occlusal surface of equine cheek teeth may develop into crown fractures.

**Objectives:** To examine the evolution of fissures present on the occlusal surface of cheek teeth. Furthermore, to investigate the presence of a fissure as a risk factor for the development of a subsequent crown fracture.

**Study Design:** Observational longitudinal study.

**Methods:** Bi-annual dental examinations were performed on 36 horses for 3 years. Video-recordings were made to evaluate the evolution of detected fissures. The effect of possible predictors on the development of tooth fractures was investigated by regression analysis.

**Results:** The evolution of 785 fissures (467 type 1a, 271 type 1b, 47 type 2) was recorded. Fissure characteristics were observed to remain unchanged, disappear, become longer, shorter, change in configuration or change in color. Partial crown fractures (22 maxillary, 50 mandibular) were recorded in 52 cheek teeth in 22/36 horses. Fifty-nine of these fractures evolved from previously observed fissures (24 type 1a, 29 type 1b, 6 type 2). All fissure types proved to be a significant risk factor for the development of a crown fracture ($p < 0.001$), with the highest odds for type 2 fissures ($OR = 14.27$; 95% CI = 4.88–41.71). Other significant risk factors were the time of follow-up ($p < 0.001$), mandibular teeth ($p < 0.001$) and the lingual side of a tooth ($p < 0.001$). All fractures were non-complicated.

**Main Limitations:** Some horses were prematurely lost for follow-up, which perhaps influenced the results. A longer follow-up period would have also allowed an evaluation of the risk for pulp disease on the long term subsequent to partial crown fractures.

**Conclusions:** The presence of a fissure of any type, mandibular cheek teeth, the lingual side of cheek teeth, and time of follow-up proved to be significant risk factors for development of a cheek tooth crown fracture. Type 2 fissures showed the highest odds followed by type 1b fissures. The observed partial crown fractures demonstrated a low clinical impact whereby no tooth showed signs of development of endodontal disease.

**Keywords: crown fracture, cheek teeth, equine dentistry, idiopathic cheek teeth fractures, fissure**

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# INTRODUCTION

Occlusal fissures, a common finding in equine cheek teeth during dental examination, are generally considered innocuous (1–3). However, in a previous study pulpitis was considered to be caused through existing occlusal fissures in 2 out of 79 (2.5%) apically infected cheek teeth (4). Oral bacteria might invade the space that is created by a fissure and colonize pulp tissue as was demonstrated by Wellmann and Dixon (5), and further supported by the findings of Pollaris et al. (6). However, it was also concluded that healthy pulp should be able to deal with these noxious stimuli (6).

Fissures have been suggested to be the early stage of crown fractures (3, 4, 7). Specifically, some fissure configurations that correspond to well-known fracture configurations (e.g., some type 1b fissures according to the classification by Pollaris et al., correspond to buccal slab fractures) (3, 8) are hypothesized to be more at risk to evolve toward a crown fracture. Ramzan and Palmer (2) stated that fissures with a largely transverse orientation [type 1a (3)] are not likely to develop into gross fractures. To the authors' knowledge, no papers have been published that studied the *in vivo* progression of fissures.

The aim of this study is to examine the evolution of fissures in time. We hypothesized that fissures may be seen as the preliminary stage for later crown fracture and that some fissure configurations are more prone to progress toward a crown fracture.

# MATERIALS AND METHODS

## Study Design

The experimental protocol was approved by the Ghent University Committee on the care and use of experimental animals in compliance with the Belgian legislation on animal experiments. Every 6 months for a period of 3 years (T0-6), a thorough dental examination was performed by the same person (EP) on each horse of a faculty-owned herd. This examination was performed on the sedated horse (detomidine; Detogesic, 15 μg/kg bwt, IV and butorphanol; Torbugesic, 15 μg/kg bwt, IV), using a full mouth speculum and an oral endoscope. Video recordings were made for retrospective analysis. The presence or absence of occlusal fissures as well as specific fissure characteristics (position of the fissure, fissure type, configuration, color) were recorded for every individual cheek tooth. Fissures were classified according to Pollaris et al. (3) as:

- Type 1a fissure: involves the secondary dentine overlying the pulp cavity and runs from the secondary dentine perpendicular to the surrounding enamel fold.
- Type 1b fissure: involves the secondary dentine overlying the pulp cavity but does not follow a perpendicular orientation in relation to one surrounding enamel fold. Often this orientation is more mesio-distal.
- Type 2 fissure: does not involve secondary dentine.

Type 2 fissures were only recorded when they involved primary dentin. Small enamel cracks which were commonly observed in a cadaveric study (3) were not included due to the difficulty to observe them on video recordings and their minimal clinical importance as has been demonstrated in a high-resolution X-ray computed tomography study (6). The development of crown fractures was recorded during the follow-up period and their relationship with previously identified fissures was noted.

Treatment of encountered dental pathology was only performed when associated with signs of oral discomfort (e.g., soft tissue lesions, periodontal disease, etc.). Prophylactic odontoplasty was not performed and the occlusion of the cheek teeth was not changed in the absence of any masticatory problem.

## Experimental Animals

Thirty-six horses were included in the study (university-owned herd), none of which had any known dental history. All horses were housed under similar conditions. Whenever possible, they were kept on pasture or otherwise stall-rested in separate boxes. As long as pasture quality allowed this, horses were not given any extras when being kept outside. When housed indoors, they were fed 1 kg of concentrates twice daily and were given hay *ad libitum*.

## Statistical Analysis

Data were recorded on a spreadsheet for descriptive statistics. Chi-square tests were used in intergroup comparisons of categorical variables (maxilla/mandible vs. fissure characteristics; fissure type vs. fissure characteristics). Categorical variables were expressed as numbers and percentages. Continuous variables were presented as mean ± standard deviation (and range, when interesting).

The effect of possible predictors on the development of tooth fractures was analyzed. The overall significance was set at $\alpha \leq 0.05$. Firstly, the effect of individual predictors (time of follow-up, gender (male/female), age, dental pathology (no pathology, wear disorder, periodontitis), maxilla/mandible, tooth (second premolar—third molar), side of the tooth (lingual/buccal), fissure present (yes/no), fissure type (no fissure, type 1a, type 1b, type 2) on the development of fractures (dependent variable, yes/no) was assessed with a generalized linear mixed model with the individual predictor as fixed effect and horse as random effect. Significance was assessed with a likelihood ratio test. *P*-values were corrected for multiple testing by multiplying them by the number of tests and are reported as such. Next, the most optimal generalized mixed model was determined based on the combination of predictors that minimized the Akaike Information Criterion. The program R version 3.5.2 ("Eggshell Igloo") was used for statistical analyses (9).

# RESULTS

Thirty-six horses (864 teeth) were included in the study at the start of the observational period (T0), including 20 mares, 14 geldings, and 2 stallions. The mean age of the horses at T0 was 12.6 (±4.55) years. The mean duration of follow-up of the horses was 2.32 (±0.98) year. Follow-up for the complete duration of the study (3 years) was possible in 22/36 animals. Follow-up records of 14/36 horses were incomplete due to reasons unrelated to this study (euthanasia, adoption). From these horses, 6 could be followed for 6 months, 2 for 12 months, 3 for 18 months, 2 for 2 years, and 1 for 2.5 years. At T0, 14/36 horses showed no dental pathology, 15/36 horses had wear disorders [wave mouth ($n = 10$), mandibular distoclusion ($n = 3$), both ($n = 2$)], and 7/36 horses had periodontal disease (2 were quidding). Horses with periodontal disease were treated with diastema debridement, corrective odontoplasty, grooving of the interproximal space and diastema occlusion with polyvinylsiloxane. During the study period, 5 teeth were extracted due to progressive periodontal disease. In 9 horses, an uncomplicated crown fracture (an enamel-dentin fracture not involving the pulp horn) was recorded at T0 in 13 teeth. In 1 horse a complicated crown fracture was present with an exposed pulp cavity [left mandibular third premolar tooth (307), partial crown fracture at the level of pulp horn 5]. This tooth showed signs of a chronic apical infection on radiographic examination and was subsequently extracted.

## General Fissure Observations

In 34/36 horses, fissures were observed at T0 with a mean of 15.64 (±15.05; range: 0–69) fissures per horse. At the start of the study (T0), 563 fissures were recorded (357 type 1a, 186 type 1b and 20 type 2) whereas 271 new fissures appeared over time (137 type 1a, 101 type 1b and 33 type 2) (**Supplementary Information 1**).

During the study, the evolution of 785 fissures could be followed of which 381 were present on maxillary cheek teeth (182 type 1a, 176 type 1b, and 23 type 2) and 404 on mandibular cheek teeth (285 type 1a, 95 type 1b, 24 type 2). Fissures were observed to remain unchanged, disappear, become longer or shorter, change in configuration (shape and/or slight positional change) or change in color (**Figure 1**). Overall, fissures remained unchanged in 67.3% (528/785), disappeared in 9.4% (74/785) and changed in length/configuration/ color in 20.8% (163/785) while the remainder fractured (**Figure 2**). The average time after which fissures disappeared after their first observation was 1.62 (±0.88) year. The fissure length increased in 7.5% (59/785) and decreased in 4.7% (37/785) of cases. Configuration changes were recorded in 5.2% (41/785). Fissure staining became darker in 3.1% (24/785) and lighter in 2.4% (19/785). A detailed overview of the distribution of these fissures can be found in **Supplementary Information 2**.

Fissure evolution was different in mandibular compared to maxillary cheek teeth, however only significantly for fissures that remained unchanged. In the maxilla, 72.4% of the fissures remained unchanged whereas in the mandible this was 62.4% ($p = 0.003$). Fissures changed in length/configuration/color in 18.1% in the maxilla and 23.3% of the mandible ($p = 0. 075$). The number of fissures that disappeared was relatively similar in maxillary (10.2%) and mandibular (8.7%) teeth ($p = 0.45$). Fissure evolution was also different between fissure types. Type 2 fissures changed in length/configuration/color more frequently (44.7%, 21/47) compared to type 1a (20.3%, 95/467) and type

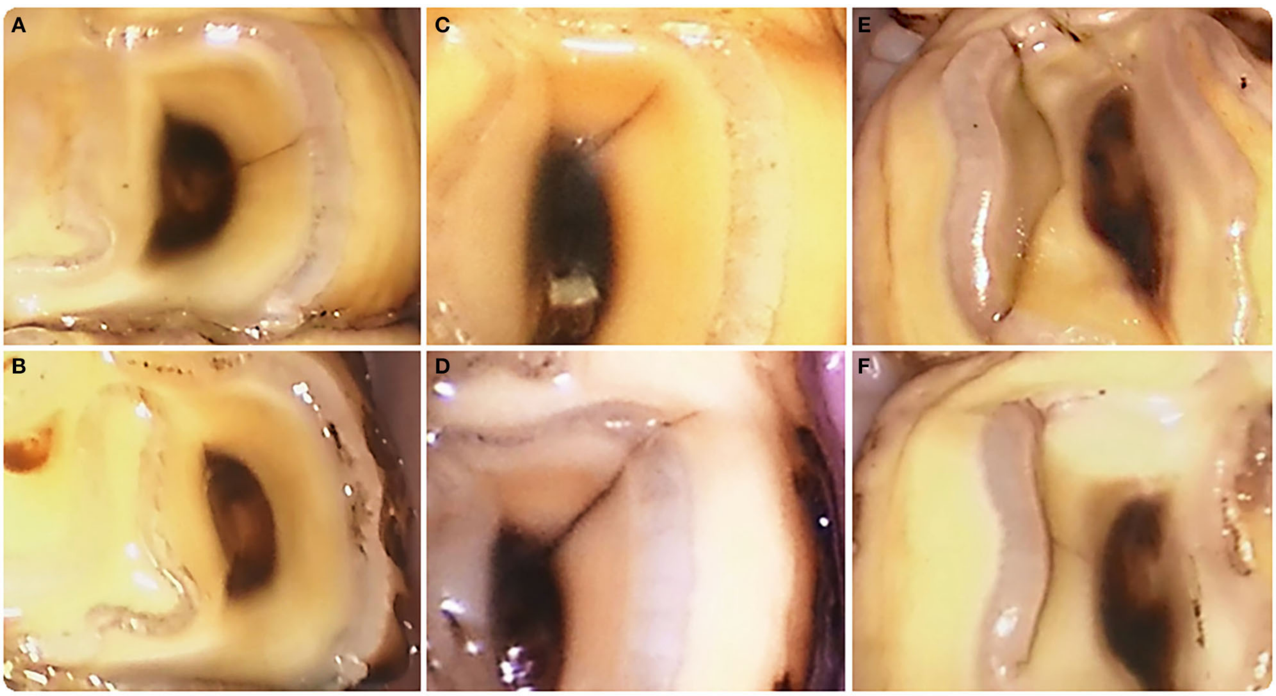


**FIGURE 1 |** Examples of fissure evolution in time. **(A)** Type 1a fissure at pulp horn 1 in a left mandibular first molar tooth (309) (T0). **(B)** This fissure had disappeared after 3 years (T6). **(C)** Type 1a fissure at pulp horn 1 in a left mandibular second molar tooth (310) (T0). **(D)** This fissure became longer after 1 year (T2) and developed into a crown fracture after 2.5 years (T5) (**Figures 3A,B**). **(E)** Type 2 fissure near the secondary dentine of pulp horn 2 in a right mandibular third premolar tooth (407) (T0). **(F)** Two and a half years later (T5) the fissure location was closer to the enamel ring. ***(A)** is top left, **(B)** is bottom left, **(C)** is top middle, **(D)** is bottom middle, **(E)** is right top, and **(F)** is bottom right*.

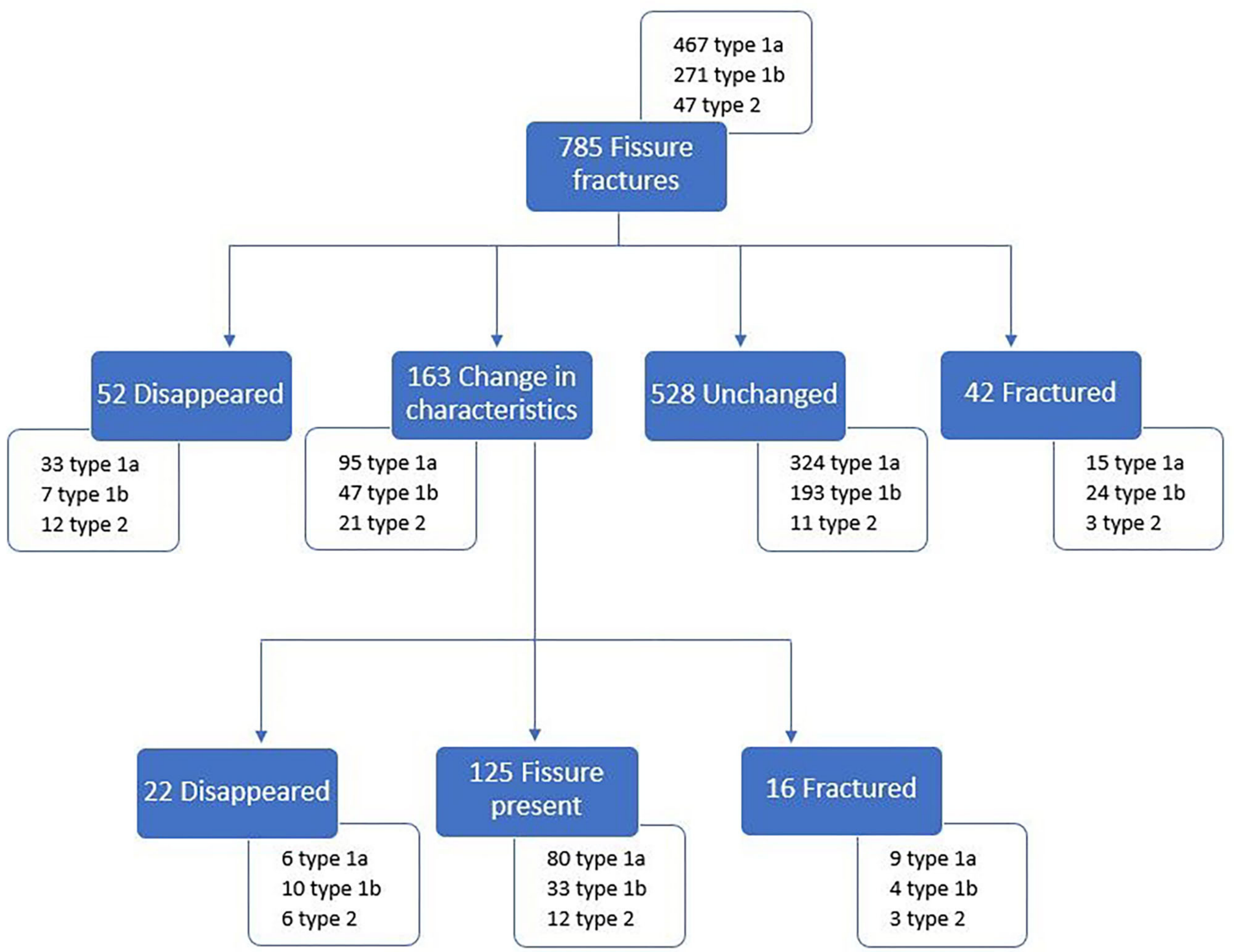


**FIGURE 2 |** Flow chart illustrating an overview of the evolution of the observed fissures.

1b (17.3%, 47/271) ($p < 0.001$). The number of fissures that disappeared was significantly higher in type 2 fissures (38.3%, 18/47) ($p < 0.001$). Type 1a and type 1b fissures disappeared in only 8.4% (39/467) and 6.3% (17/271), respectively. An overview of the observations in the maxillary and mandibular arches of fissures that changed in length/configuration/color is given in **Supplementary Image 1**.

## Crown Fractures

During the follow-up period, 22/36 horses developed a partial crown fracture in 52 different cheek teeth (18 maxillary and 34 mandibular cheek teeth) with an average of 1.38 (±0.72) fractures per tooth. In total, 72 crown fractures (22 maxillary, 50 mandibular) were observed. Crown fractures in teeth without the previous detection of a fissure were observed in 13 cheek teeth (9 mandibular, 4 maxillary cheek teeth), which were all on the lingual side of the tooth (**Supplementary Image 2**). Fifty-nine crown fractures originated from a previously identified fissure (24 type 1a, 29 type 1b, and 6 type 2) (**Figure 3**). One type 1b fissure fractured twice in a different location of the fissure at different time points. Overall, fissuresevolved to a partial crown fracture in 7.4% (58/785). The average time that elapsed between the initial observation of a fissure and the development of a partial crown fracture was 1.36 (±0.91) years. Crown fractures originating from fissures involved maxillary teeth in 18/59 (30.5%) and mandibular teeth in 41/59 (69.5%) of fracture cases. These fractures occurred on the buccal side in 26/59 (44.1%) teeth (7 maxillary, 19 mandibular) and on the lingual side in 33/59 (55.9%) teeth (11 maxillary, 22 mandibular).

The detailed results of the potential association of variable predictors with the presence of a tooth fracture can be found in **Table 1**. Individual factors that were associated with fracture development included follow-up time ($p < 0.001$), dental pathology ($p < 0.05$), maxilla/mandible ($p < 0.01$), the presence of a fissure ($p < 0.001$), and fissure type ($p < 0.001$). Gender ($p = 1$), Tooth type ($p = 0.08$), fissure on the buccal or lingual side of the tooth ($p = 0.07$), and age of the horse ($p = 1$) were not found to be significant. After construction of the final model,

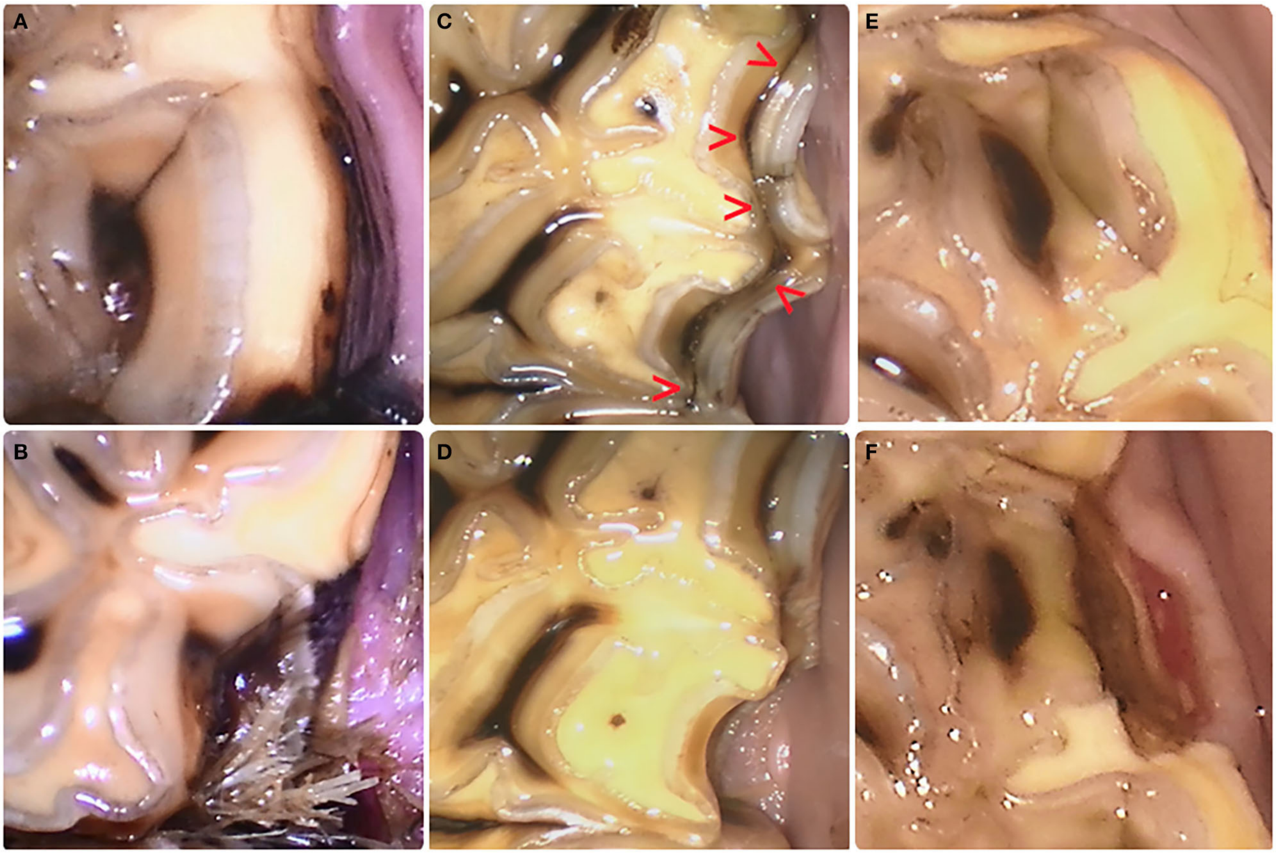


**FIGURE 3 |** Evolution from fissure to crown fracture. **(A)** Type 1a fissure at the level of pulp horn1 in a left mandibular second molar tooth (310) with subsequent fracture development after 2.5 years. Food impaction between teeth at the fracture site is visible **(B)**. **(C)** This Type 1b fissure (red arrow heads) connecting pulp horn1 and pulp horn2 in a left maxillary fourth premolar tooth (208) evolved toward a partial buccal slab fracture at the level of pulp horn 2 **(D)** after 2.5 years. **(E)** Type 2 fissure located buccal to pulp horn 2 of a left mandibular third premolar tooth (308) resulted in a fracture **(F)** 6 months later. The recent nature of the fracture is evident through the damaged gingival margin. ***(A)*** *is top left,* ***(B)*** *is bottom left,* ***(C)*** *is top middle,* ***(D)*** *is bottom middle,* ***(E)*** *is right top, and* ***(F)*** *is bottom right*.

time of follow-up ($p < 0.001$), maxilla/mandible ($p < 0.001$), fissure type ($p < 0.001$), and the side of the tooth ($p < 0.001$) remained significantly associated with the presence of a tooth fracture (**Table 2**). Horses with a longer follow-up showed higher odds of presenting a tooth fracture ($OR = 3.37$; 95% CI, 1.71–6.66). Partial crown fractures were more frequently observed in mandibular cheek teeth (69.4%, 50/72) compared to maxillary cheek teeth (30.6%, 22/72). The odds for a maxillary cheek tooth to fracture was 0.43 (95% CI, 0.20–0.59) times smaller compared to mandibular cheek teeth whereas the lingual side of a cheek tooth showed 2.56 (95% CI, 1.50–4.34) times higher odds to fracture. Teeth showed 4.75 (95% CI, 2.29–9.87), 11.06 (95% CI, 5.47–22.35), and 14.27 (95% CI, 4.88–41.71) higher odds to fracture when a type 1a, type 1b and type 2 fissure were present, respectively.

When inspecting the appearance of fissures prior to fracturing it was observed that all fissures that evolved into a partial crown fracture involved or crossed the outer enamel ring. Fissure characteristics remained unchanged in the majority of these fissures before fracturing (42/58; 72.4%) (**Figure 2**). Sixteen fissures changed in characteristics before fracturing including 10 becoming longer, 1 becoming shorter, 2 changing their configuration, 1 becoming longer and changed in configuration and 2 changing color (1 darkened and 1 became lighter).

Fracture patterns varied between fissure types (**Figures 4**, **5**). Fractures evolving from type 1a fissures were more often located in the "corners" of the cheek teeth. A more diverse fracture pattern was recorded when evolving from type 1b fissures. These fractures were mostly located on the lingual side of the tooth (20/29). They were observed on the buccal side of the tooth in 9/29 cases, with one complete buccal slab fracture of a left maxillary third molar tooth (211). Fractures originating from type 2 fissures were recorded on the distolingual side of the tooth in 4/6 cases.

Only one horse developed clinical symptoms (head tilt while eating) related to a crown fracture. In this case, the fractured fragment [buccal slab, left maxillary third molar tooth (211)] was present and caused a lesion in the adjacent mucosa of the cheek. After removal of the fragment the horse showed no further symptoms. The other fractures were only noted at the predetermined time points for follow-up with the fracture fragment already missing. In 13/72 cases, local inflammation of

**TABLE 1 |** Results of the association analysis of individual variables with the presence of a tooth fracture.

| Tooth fracture | | | | |
|---|---|---|---|---|
| **Variable** | **Category** | **Estimate** | **SE** | **95% CI** |
| **Time of follow-up** | Cont. | 1.38 | 0.37 | 0.66–2.10 |
| **Pathology** | No pathology | Reference category | | |
| | Periodontitis | 0.67 | 0.66 | −0.62–1.97 |
| | Wear disorder | 1.56 | 0.54 | 0.51–2.62 |
| **Jaw** | Mandible | Reference category | | |
| | Maxilla | −0.86 | 0.26 | −1.37 to −0.34 |
| **Fissure present** | Yes | Reference category | | |
| | No | −1.91 | 0.33 | −2.56 to 1.28 |
| **Fissure type** | No | Reference category | | |
| | 1a | 1.48 | 0.37 | 0.75–2.21 |
| | 1b | 2.22 | 0.36 | 1.53–2.92 |
| | 2 | 2.59 | 0.55 | 1.52–3.66 |

**TABLE 2 |** Final model of all variables associated with a tooth fracture.

| Tooth fracture | | | | |
|---|---|---|---|---|
| **Variable** | **Category** | **Estimate** | **SE** | **95% CI** |
| **Time of follow-up** | Cont. | 1.22 | 0.35 | 0.53–1.90 |
| **Jaw** | Mandible | Reference category | | |
| | Maxilla | −1.07 | 0.27 | −1.60 to −0.53 |
| **Fissure type** | No | Reference category | | |
| | 1a | 1.56 | 0.37 | 0.83–2.29 |
| | 1b | 2.40 | 0.36 | 1.70–3.11 |
| | 2 | 2.66 | 0.55 | 1.58–3.73 |
| **Tooth side** | Buccal | Reference category | | |
| | Lingual | 0.94 | 0.27 | 0.41–1.47 |

the surrounding gingiva demonstrated the recent nature of those fractures. During the study period, none of the horses developed a complicated fracture characterized by communication with the adjacent pulp cavity.

## DISCUSSION

With the routine use of oral dental scopes by equine dental specialists, small dental anomalies are easily detected but subsequently raises more questions on the clinical importance of these observations. The presence of fine linear defects in the occlusal surface of equine cheek teeth is one of them and it has been demonstrated that these macroscopically visible fissures are in fact true microscopical cracks in the tooth (5, 6). Some authors suggested that occlusal fissures might evolve to crown fractures (3, 4, 7), which is supported by the results of this study (7.4% of fissures evolved to a partial crown fracture in this study population). Equine cheek teeth fractures are major dental lesions and a topic of interest for many researchers. Dental fractures occur in all equine teeth with a low prevalence (0.4–6%) reported in cheek teeth (10, 11). However, this study population demonstrates that horses might develop (uncomplicated) crown fractures more frequently (22/36 horses developed at least one crown fracture). A possible explanation for the relatively high incidence of crown fractures in this population is the set-up of this study with specific attention for crown fractures and using an oral scope in all horses. The observed fractures in this study consisted of low impact partial crown fractures of very limited clinical importance and subsequently remaining without obvious signs of oral discomfort. These fracture types might thus be overlooked during routine dental examinations and not recorded on dental record forms. Therefore, the true prevalence of different cheek tooth fractures might be higher in the general population than previously reported due to a more selective recording of relevant dental pathology.

During the study period, identified fissures were observed to remain unchanged, to disappear and to change in configuration, in length or color demonstrating the dynamics that occur in the occlusal surface of equine cheek teeth due to the continuous grinding action during mastication. Type 1a and type 1b fissures predominantly remained unchanged (69 and 71%, respectively), while this was only the case in 23% of type 2 fissures. Type 2 fissures disappeared in 38% as opposed to only 8% of type 1a and 6% of type 1b fissures. The authors suggest that fissures that became shorter or lighter in color over time were more likely to disappear, which seems particularly true for type 2 fissures where 5/10 fissures that became shorter also disappeared. However, due to the relative low number of observations of fissures becoming lighter (19/785) or shorter (38/785) it is not possible to make definite conclusions on this matter. None of the fissures that became longer during the study disappeared during the follow-up period.

A total number of 72 crown fractures were recorded of which 59 developed at the level where before a fissure had been identified. All fissure types proved to be a significant risk factor for a tooth to develop a crown fracture at that specific location. Furthermore, it was shown that type 2 fissures had the highest odds to evolve into a crown fracture with 13% observed to fracture followed by type 1b (10%) fissures. These findings support previous hypotheses that fissures with patterns in a more mesio-distal plane are more prone to develop into gross crown fractures (3, 4, 6, 7, 12). In contrast, fissures with a largely transverse orientation (type 1a) were also observed to develop into crown fractures (5%). Clinically it remains impossible to predict with certainty which fissures will evolve into a crown fracture. However, it was observed that all fissures that evolved into a crown fracture only involved the marginal ridge(s) of the tooth. It might be suspected that fissures that became darker might be more susceptible to fracture since this darker color might indicate a higher uptake of plant material and thus a wider fissure gap. However, only 1/24 fissure that became darker was observed to fracture afterwards. Similarly, it might also be suspected that fissures that became longer might be more susceptible to fracture since they might further weaken the tooth, which was the case in 11/59 fissures. Unfortunately, due to the relative low number of observations of fissures becoming darker (24/785) or longer (58/785), it is not possible to draw

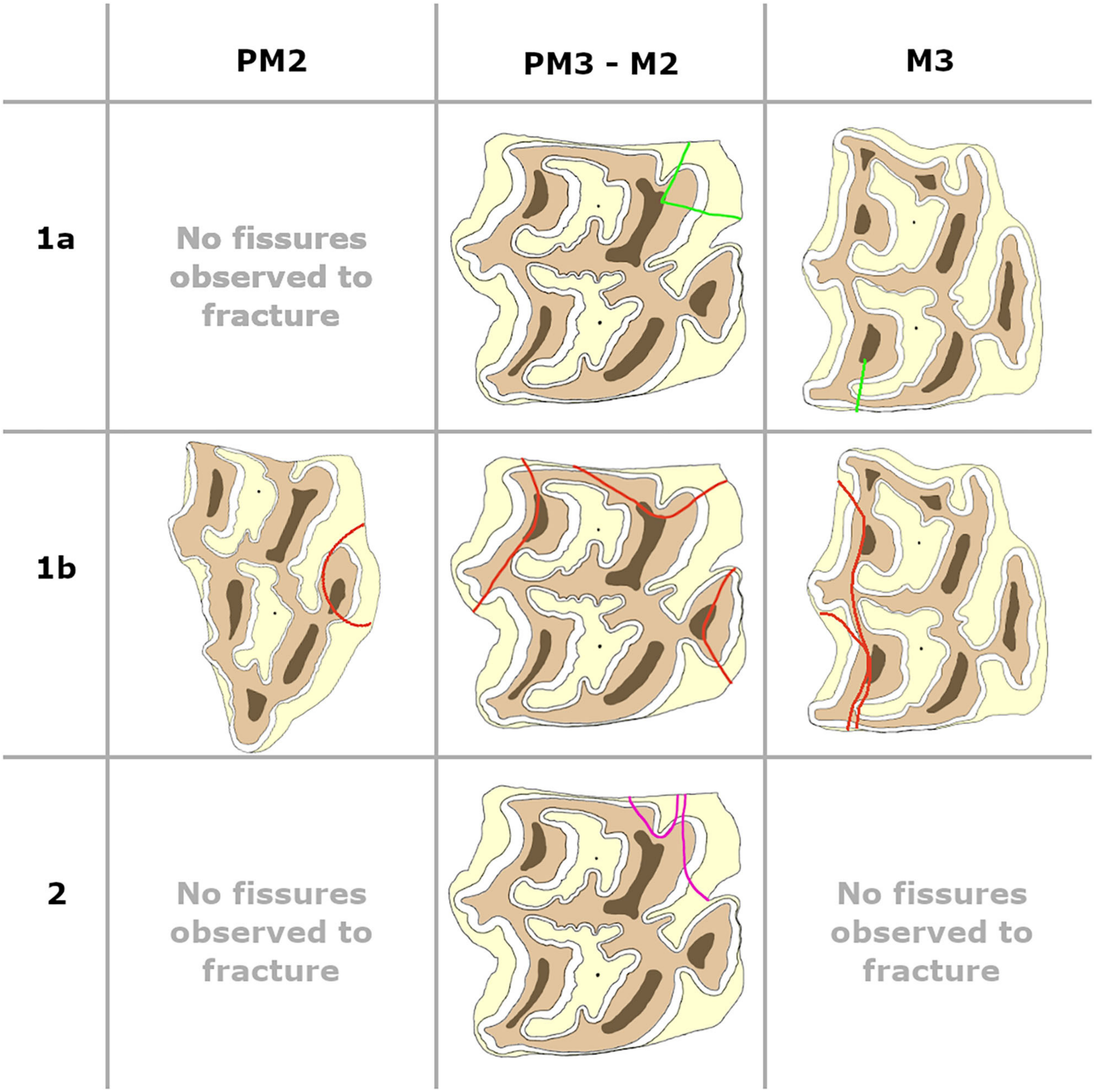


**FIGURE 4 |** Fissure patterns observed to fracture in maxillary cheek teeth. Left is buccal, right is lingual, top of the picture is distal and the bottom of the picture is mesial.

firm conclusions in this matter. Fracture configurations of crown fractures without previously detected fissures showed similar fracture patterns compared to crown fractures that did develop from previously identified fissures (mainly type 1b). Therefore, we hypothesize that they share a similar etiopathogenesis. Several studies have been performed describing the characteristics of the most common fracture planes (8, 10, 13). The most common "idiopathic" cheek teeth fractures are buccal slab fractures in maxillary and mandibular cheek teeth through the secondary dentine of pulp horns 1 and 2. Additional less common maxillary and mandibular miscellaneous fracture patterns have also been observed (8). In the present study population, only one complete buccal slab fracture was observed in a left maxillary third molar (211) tooth, however partial buccal slab fractures (only involving the secondary dentin of pulp horn 1 or 2) were detected more frequently. In maxillary cheek teeth, this type of fracture was one of the most common fracture patterns involving the secondary dentine of pulp horn 2 (4/18). Other fracture types in maxillary cheek teeth were observed at the lingual side which did not match the fracture patterns described by Dacre et al. In contrast to the

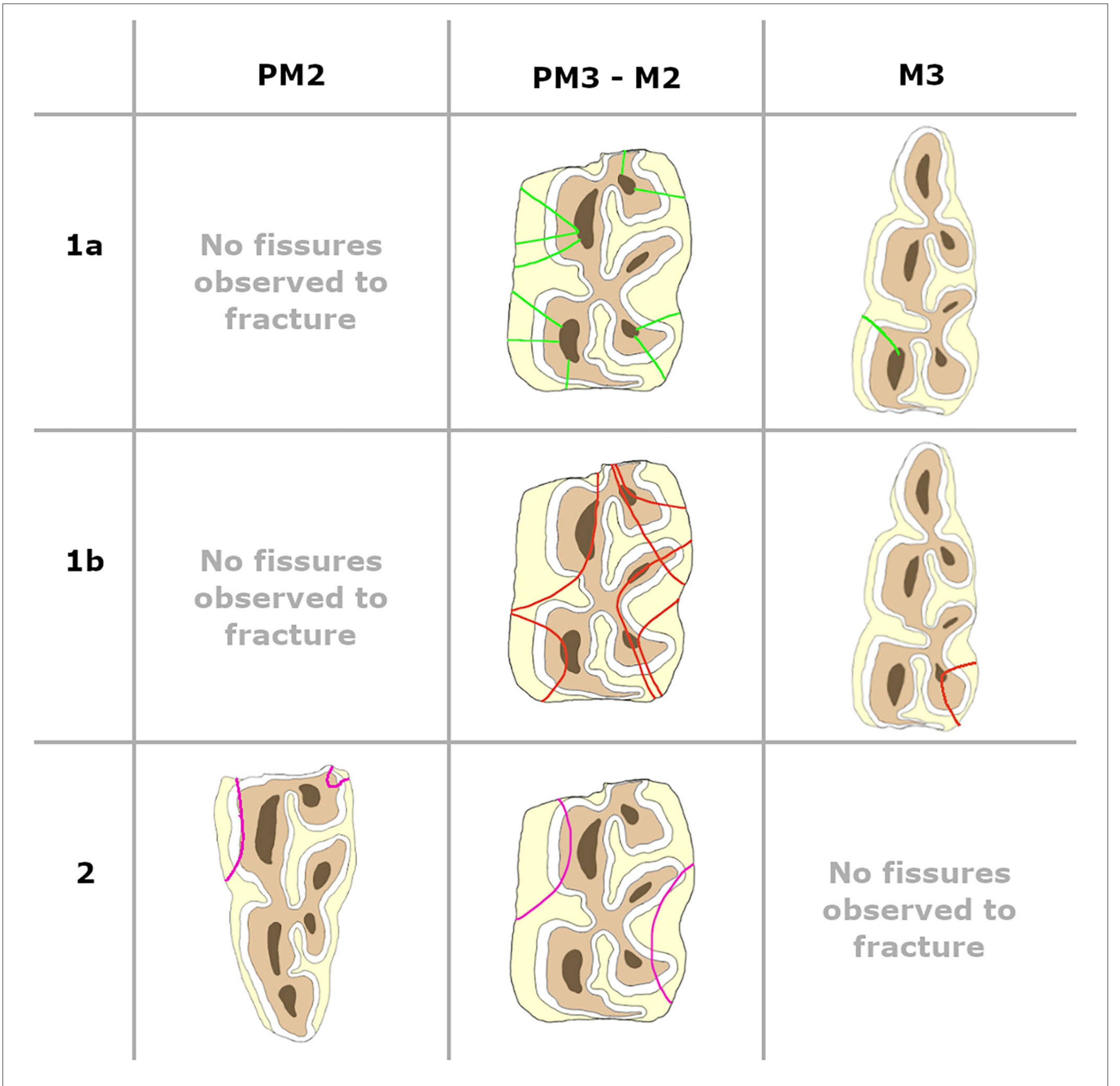


**FIGURE 5 |** Fissure patterns observed to fracture in mandibular cheek teeth. Left is buccal, right is lingual, top of the picture is distal and the bottom of the picture is mesial.

findings of these authors (8), the most common fracture site in mandibular cheek teeth was located on the lingual side (at the level of pulp horn 3 or 5) (14/41). In this study, mandibular cheek teeth had significant higher odds to develop a tooth fracture, but no predilected teeth was found. This is in contrast with other studies where the maxillary third premolar, first and second molar (triadan 08, 09, 10) and mandibular third premolar and first molar (triadan 08 and 09) teeth were noted to be most commonly involved in crown fractures (8, 10, 13). Cheek teeth in this study were found to have higher odds to fracture on the lingual side of the tooth which again is in contrast with findings of other studies who found that fractures were more frequently found on the buccal side of the tooth (8, 10, 13).

It has been suggested that occlusal fissures are induced by masticatory forces and that due to the interactive mechanical supportive role of the different dentinal tissues, some anatomical locations on the occlusal surface are more prone to mechanical trauma (3, 6). The lingualside of equine maxillary cheek teeth is indeed the position where the masticatory forces are the highest in the maxilla. In contrast, the lingual side of mandibular cheek teeth is not (14). However, when looking at tooth anatomy, there are more enamel infoldings on the lingual side of the mandibular tooth with thinner enamel which might render this side of the tooth weaker (15, 16). The emergence of new fissures in time also supports the suggested theory that fissures are caused by masticatory forces. The presence of dental pathology such as abnormalities of wear was not withheld as a significant risk factor which supports a previous finding that an abnormal wear pattern does not necessarily have a promoting influence on the development of fissures (3). Ramzan and Palmer stated that there was no suggestion that a previous prophylactic dental treatment was a factor in the development of the fissures they observed (2). In the present study, the possible interference of dental treatments on masticatory forces was limited as much as possible by not performing odontoplasty during the study period except when there were signs of clinical discomfort (e.g., oral lesions). This might have had an influence on the occurrence and evolution of detected fissures in the study population.

The aetiopathogenesis of sagittal midline fractures of maxillary cheek teeth has been traced back to severe infundibular caries and are nowadays termed caries-related infundibular fractures (17). In teeth with (idiopathic) fractures that involve pulp horns (e.g., buccal slab fracture), the underlying cause has not been discovered yet. In one study, a reduced dentinal thickness was observed in 25% of these cases indicating that these teeth probably had prior pathological changes with the fracture being a consequence of dental disease rather than a primary pathology (8). Conversely, other studies suggested that fractures involving pulps (including fissures) were the cause for an apical infection in 20% of mandibular cheek teeth and 9% in maxillary cheek teeth (12, 18). It has been shown that many idiopathic fractures do not result in signs of pulpitis or apical disease (4, 10, 13). None of the horses in the present study developed a fracture-related apical infection, and in none of the fractured teeth, a direct communication with the pulp cavity could be found. These findings support the assumption of Dacre et al. that idiopathic crown fractures that communicate with underlying pulp cavities are more likely a secondary pathology of prior dental disease (8).

The clinical sequela most often related with cheek tooth fractures is oral pain caused by mucosal trauma or food pocketing, and periodontitis around the fractured tooth (10, 13). In this study, one horse showed clinical symptoms related to a tooth fracture (head tilt while eating). In this case, the tooth fragment at the level of the fracture (buccal slab, left maxillary third molar [211] tooth) was present causing mucosal trauma of the cheek. After removal of the fragment, the horse showed no further signs of oral discomfort. None of the other horses showed clinical symptoms related to a tooth fracture (2 horses were quidding in the beginning of the study period related to periodontal disease), however it is possible that acute, temporary clinical manifestation of symptoms might have been missed in the horses while they were on pasture. Only in 13/72 cheek tooth fractures, limited local inflammation of the surrounding gingiva was observed in this study population which supports that these partial crown fractures have a low clinical impact. While some equine cheek teeth fractures may result in apical disease (12, 18), more often they do not as is supported by the present study where none of the horses developed a fracture-related apical infection. These results once again reflect the remarkable capability of the equine dentine-pulp complex in walling off the oral environment subsequent to a noxious stimuli.

This research, however, is subject to some limitations. Some horses were prematurely lost during the study period which possibly influenced the outcome of the analysis. The results of this study are furthermore quite population-specific. Nevertheless, the obtained results demonstrate that fissures can evolve into partial crown fractures as we hypothesized. Secondly, during the study period of 3 years none of fractured teeth showed indications of being endodontically compromised. However, a longer follow-up period would have allowed a more extensive evaluation of the risk for pulp disease. Another way to help determine if endodontal disease, such as low grade pulpitis, might have been present was to perform a computed tomography scan.

## CONCLUSION

The presence of a fissure of any type, mandibular cheek teeth, the lingual side of cheek teeth and time of follow-up proved to be significant risk factors for development of a cheek tooth crown fracture. Type 2 fissures showed the highest odds followed by type 1b fissures. The observed partial crown fractures in this study demonstrated a low clinical impact whereby no tooth developed signs of endodontal disease during the follow-up period.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Materials**, further inquiries can be directed to the corresponding author.

## ETHICS STATEMENT

The animal study was reviewed and approved by Ethic committee of the Faculty of Veterinary Medicine Ghent University.

## AUTHOR CONTRIBUTIONS

LV and EP designed the study. EP performed the execution of the study (dental examinations and processing data), BB analyzed the data. EP, LV, and BB interpreted the findings. EP and LV prepared the manuscript. All co-authors contributed and approved the final version of the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.604420/full#supplementary-material

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
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# Equine "Idiopathic" and Infundibular Caries-Related Cheek Teeth Fractures: A Long-Term Study of 486 Fractured Teeth in 300 Horses

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**Background:** Limited objective information is available on the prevalence of non-traumatic equine cheek teeth fractures, the signalment of affected horses, and the clinical features and treatment of these fractures.

**Objectives:** This study aims to document patterns of idiopathic and infundibular caries-related cheek teeth fractures in a referral population and evaluate associations between fracture patterns and horse age, Triadan position of affected teeth, clinical signs, and deemed necessity for treatment.

**Study Design:** A retrospective case review.

**Methods:** The clinical records at Edinburgh University Veterinary School (2010–2018) were examined for the presence of non-traumatic equine cheek teeth fractures. Variations in the frequencies of different fracture patterns were compared between horse ages, Triadan tooth positions, clinical signs, and deemed necessity for treatment.

**Results:** Records of 300 horses with 486 non-traumatic cheek teeth fractures including 77% maxillary and 23% mandibular teeth with a mean of 1.6 (range 1–10) fractured teeth/horse were available. Fracture patterns included maxillary first and second pulp horn ("slab") cheek teeth fractures ($n = 171$), caries-related infundibular fractures ($n = 88$), other maxillary teeth fracture patterns ($n = 92$), mandibular first and second pulp horn ("slab") fractures ($n = 44$), other mandibular fracture patterns ($n = 62$), and complete clinical crown loss ($n = 29$; including 23 maxillary and 6 mandibular teeth). The median age of affected horses ranged from 11 years with maxillary "slab" fractures to 15 years with infundibular caries-related fractures. Triadan 08–10s were the most commonly (86%) fractured maxillary teeth. The Triadan 08 and 09 positions were the most commonly (64%) fractured mandibular teeth. No clinical signs were noted in horses with 48% of the fractured teeth; oral pain/quidding was recorded with 26%, clinical apical infection with 23%, and bitting/headshaking problems with 6%. Treatments included extraction of 40% fractured teeth, extraction of small/loose fragments (10%), and odontoplasty. Stable remnants of 60% of fractured teeth were left in horses without clinical signs.

**Main Limitations:** Long-term follow-up information was not available for all cases.

**Conclusions:** There is increasing recognition of equine non-traumatic cheek teeth fractures, with about half not causing clinical signs. Teeth with apical infection, multiple fractures, or advanced caries require extraction. Other fractured teeth with subclinical endodontic disease may not need exodontia unless they later cause clinical signs.

**Keywords: horse, equine dental disease, equine dental fractures, equine idiopathic cheek teeth fractures, infundibular caries-related dental fracture**

## INTRODUCTION

Most equine cheek teeth fractures occur in the absence of known evidence of trauma and have been termed *idiopathic* cheek teeth fractures (1). These fractures most commonly affect the maxillary cheek teeth, especially the Triadan 09 position (1–4), and a pathological study showed 25% of these teeth to have had chronic endodontic disease prior to fracturing (2). More recently, a subset of these fractures, i.e., midline sagittal fractures of maxillary cheek teeth, has been recognized to be caused by coalescence of deeply carious infundibula (5–7), and these have now been termed *infundibular caries-related (sagittal) fractures* (8).

The fracture planes in the remaining non-traumatic (idiopathic) cheek teeth fractures always run through one or more pulp horns causing direct pulpar exposure (i.e., are *complicated* dental fractures) in a variety of patterns (2). The most common pattern, colloquially termed a *slab* or *buccal slab* fracture, is a thin sagittal buccal fracture of the clinical crown only, through the first and second (buccal) pulp horns of maxillary teeth (1–4, 9). A variety of other, less common maxillary teeth fracture planes, involving one or more pulp horns, can also occur (1–4).

Idiopathic fractures less commonly occur in mandibular cheek teeth, where the most prevalent pattern is also a sagittal ("slab") fracture through the first and second pulp horns (1–4). Because mandibular cheek teeth do not have infundibula, this fracture plane lies closer to the sagittal midline and these fractures can clinically appear as "midline" sagittal fractures. A variety of other fracture planes through pulp horns occur less commonly (1–4).

Fracture sites can fill with food, which, along with masticatory movements, displaces smaller or more mobile dental fragments which can cause lingual or buccal lacerations, in addition to overstretching the periodontal ligaments. These soft tissue insults can cause oral pain with resultant quidding, loss of appetite, and bitting and headshaking problems. Spontaneous loss or extraction of displaced or mobile fragments usually resolves the oral pain (3, 4).

If a fracture-related pulpar exposure is not sealed off with tertiary dentine, pulpar, or apical infection may develop causing clinical signs such as unilateral nasal discharge and maxillary or mandibular swellings. Some fractured cheek teeth not causing clinical signs of apical infection have evidence of apical infection and alveolar remodeling on radiography (authors' unpublished observations). Rowley et al. (10) showed that 77% of all such fractured cheek teeth had apical changes on computed tomographic (CT) imaging. Due to continued dental eruption and wear, and in the absence of any further subocclusal secondary dentine deposition, occlusal pulpar exposure may later become apparent in some remaining non-fractured pulps, confirming death of these exposed pulp(s). In contrast, the exposed pulp horns in other fractured teeth become fully sealed off by tertiary dentine, and apparently, normal dental function continues (authors' unpublished observations).

## MATERIALS AND METHODS

The clinical and imaging records of horses undergoing dental examination (some on multiple occasions over many years) at The University of Edinburgh Equine Hospital between 2010 and 2018 were retrospectively examined for the presence of non-traumatic cheek teeth fractures, i.e., where there was no history or clinical evidence of these fractures being due to external trauma or iatrogenic damage. Horses with fissure (hairline) cheek teeth fractures were not included in this study. Horses that had other major dental-related disorders (such as a dental sinusitis or oro-maxillary fistulas unrelated to a fractured tooth, or severe diastemata-related periodontal disease) were excluded, to allow meaningful assignment of clinical signs to any detected fractured teeth. In horses with more than one fractured cheek tooth, the more generalized clinical signs such as quidding or headshaking were assigned to every fractured tooth present at that examination if there was no clear evidence to assign the clinical signs to one tooth, such as an acute onset oral pain/quidding caused by a recent maxillary cheek tooth "slab fracture." More specific clinical signs such as unilateral nasal discharge due to dental sinusitis or swellings of the supporting bones were only attributed to the teeth shown to have clinical apical infection by detailed clinical and imaging examinations.

The recorded treatment for fractured cheek teeth that were examined more than once was the last treatment given for that dental fracture. For example, a fractured tooth may have initially been treated by extraction of displaced and/or mobile fragments present (and usually odontoplasty of sharp edges of the fractured and possibly of the adjacent and opposing teeth). However, if clinical signs of apical infection or further fractures developed later, the teeth were then fully extracted, and the latter was the recorded treatment for the purpose of this study.

### Statistical Analyses

Data were summarized and presented as mean/median and ranges. Normality of variables was assessed (where appropriate) graphically using Shapiro–Wilks tests. Non-parametric tests were used for variables that were not normally distributed.

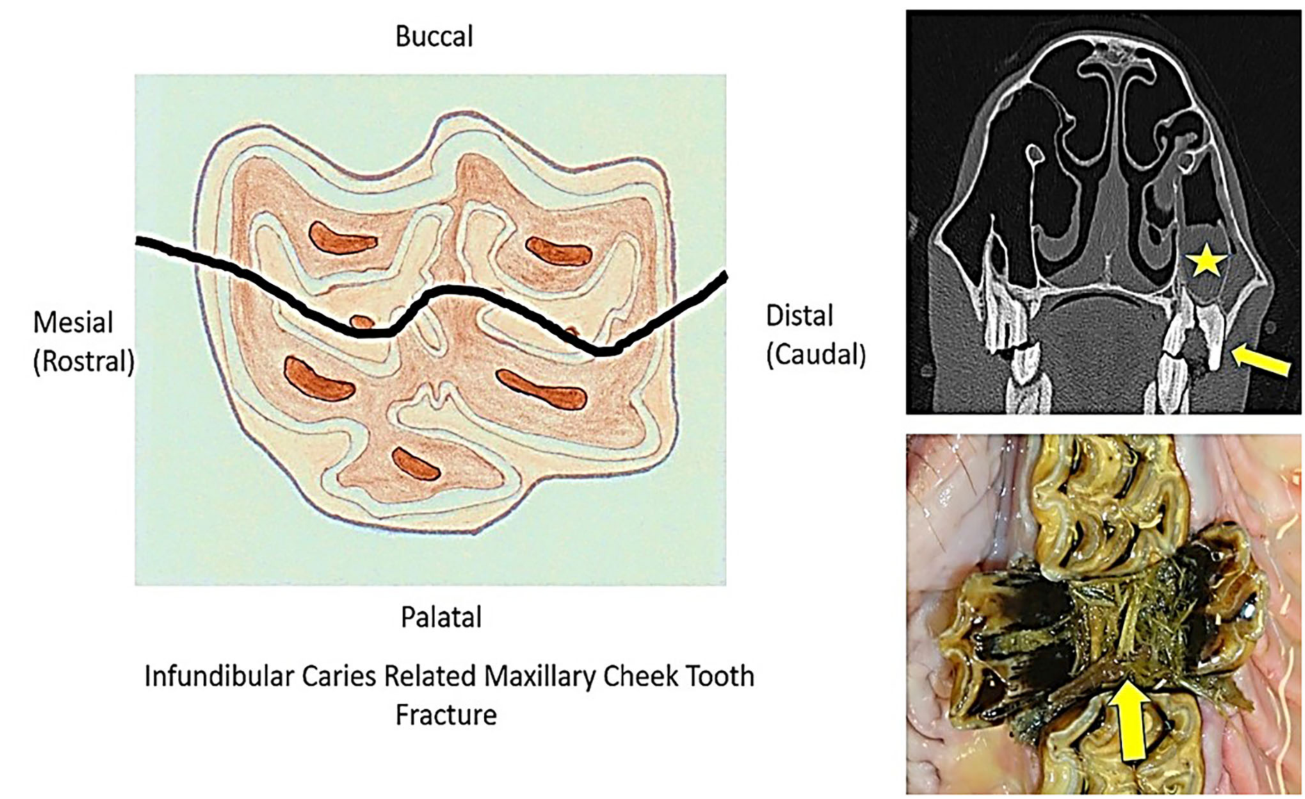


**FIGURE 1 |** The diagram on the left shows the fracture plane through both infundibula (that would have advanced caries and likely coalescence of both infundibula before fracturing). The top right image shows a transverse computed tomographic image of an aged Triadan 209 with a midline infundibular caries-related sagittal fracture (arrow) with resultant apical infection and maxillary sinusitis (star). The bottom right image shows a postmortem image of an infundibular caries-related midline sagittal Triadan 109 fracture with palatal and buccal displacement of the two fracture fragments and food impaction in the fracture site (arrow).

The association between fracture type and age was assessed using a Kruskal–Wallis rank sum test, followed by pairwise comparisons between fracture types using Wilcoxon rank sum tests.

Chi-squared tests were used to evaluate the associations between Triadan tooth position and frequency of infundibular caries-related fracture (maxillary teeth) or idiopathic fracture and between fracture type and frequency of tooth extraction.

A Fisher's exact test was used to evaluate the association between mandibular tooth position (explanatory variable) and frequency of any types of dental fractures (outcome variable). Odds ratios were calculated between groups using an unconditional maximum likelihood estimation, with small sample adjustment when group sizes were $<5$.

Univariable logistic regression models, with horse as a random effect, were produced to evaluate associations between the outcomes "oral pain" (that for the purpose of this analysis included all horses with oral pain/quidding and bitting problems) and nasal discharge and the explanatory variable fracture types, while accounting for the potential effect of multiple fracture types in the same horse.

Statistical analyses were performed in RStudio$^{TM}$. Significance was set as $P < 0.05$.

## RESULTS

## Numbers of Fractured Teeth per Case

Complete clinical records of 300 horses with 486 non-traumatic cheek teeth fractures [374 (77%) maxillary and 112 (23%) mandibular teeth] were available with a mean of 1.6 (range 1–10) fractured teeth per horse. A single fractured tooth was present in 206 horses: two in 59 horses, three in 16 horses, four in 10 horses, five in 5 horses, six in 3 horses, seven in 3 horses, and 10 fractured teeth in 1 horse. Long-term follow-up information was collected by a written questionnaire (in a separate exodontia study) only on cases that had the fractured teeth extracted a mean of 5.9 years (standard deviation 3.1 years) following extraction. Informal follow-up information was collected on some other cases.

## Fracture Patterns

### Infundibular Caries-Related Cheek Tooth Fractures

Infundibular caries-related (midline) sagittal fractures were present in 88 (18.1% of fractured teeth) maxillary cheek teeth, with both fragments present in 84/88 (95%) teeth and a single fragment present in 4/88 (5%) teeth (**Figure 1**).

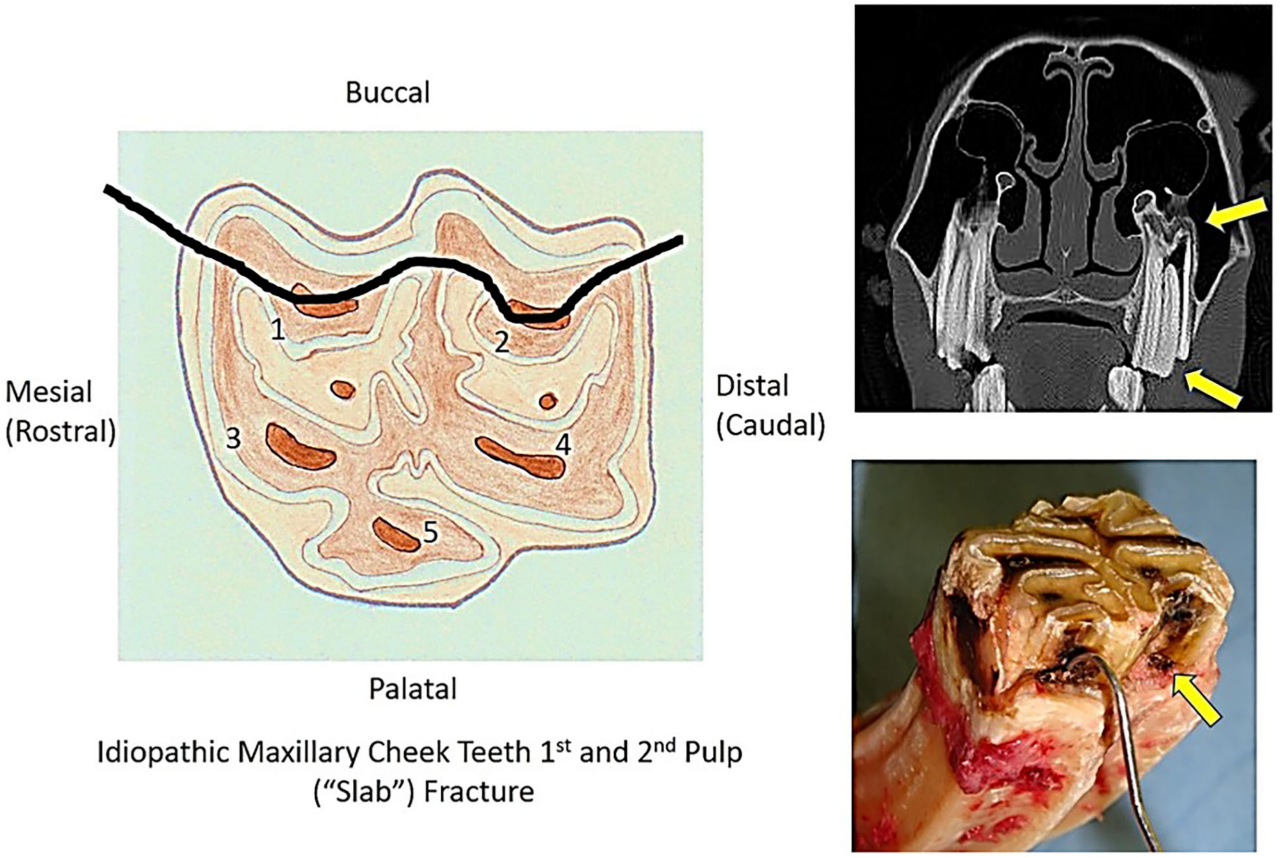


**FIGURE 2 |** The diagram on the left shows the maxillary cheek teeth pulp horn positions and the site of a fracture plane through pulp horns 1 and 2 (buccal "slab" fracture). Top right is a transverse computed tomographic image of a young Triadan 209 with a buccal "slab" fracture (bottom arrow). There is a resultant apical infection as evidenced by hypoattenuation of an affected pulp horn and, more so, of the common pulp chamber. The affected alveolus and the overlying maxillary sinus mucosa are remodeled and swollen, respectively (top arrow). The bottom left image shows a fractured maxillary cheek tooth extracted because of clinical apical infection. It has occlusal pulpar exposure of the first pulp horn (containing probe) and the second pulp horn (arrow).

### Maxillary First and Second Pulp Horn ("Slab") Fractures

The most common maxillary (and overall) cheek teeth fracture pattern was a fracture of the clinical crown only, through the first and second pulp horns ("slab" or "buccal slab" fracture) ($n$ = 171; 35.2% of all fractures) (**Figure 2**). The smaller buccal fragments were missing in 162/171 (95%) cases, and horses that had recently lost the buccal fragment had adjacent gingival damage and usually buccal ulceration.

### Miscellaneous Other ("Atypical") Maxillary Cheek Teeth Fractures

Twenty-eight other different ("atypical") patterns of maxillary cheek teeth fractures were recognized in 92 teeth that had some remaining clinical crown, usually with loss of smaller fracture fragments. The six most commonly recognized atypical fracture patterns are shown in **Figure 3**. These fractures usually involved single pulp horns, including pulp horn 1 ($n$ = 16; 17% of identified atypical fracture patterns), pulp horn 2 ($n$ = 25; 27%), pulp horn 3 ($n$ = 8; 9%), pulp horn 4 ($n$ = 7; 8%), pulp horn 5 ($n$ = 1; 1%), and pulp horn 6 ($n$ = 1; 1%). Two pulp horns were fractured in 13 teeth with 7 different fracture patterns, 3 pulps in 6 teeth with 5 different patterns, and 4 pulp horn fractures in 2 teeth with 2 different patterns. Eight teeth had different combinations of fractures through pulp horns and a single infundibulum. Five other teeth were classified as "atypical maxillary" in the records without further identification of their fracture pattern. Overall, the buccal pulps were most commonly involved, with various combinations of fractures of the first pulp horn present in 39 teeth, of the second pulp horns in 46 teeth, of the third pulp horn fractures in 30 teeth, of the fourth pulp horns in 32 teeth, and of the fifth pulp horns in 23 teeth.

### Mandibular First and Second Pulp Horn ("Slab") Fractures

The most common fracture pattern in mandibular cheek teeth was also a fracture through the first and second pulp horn ("slab") fractures ($n$ = 44), often extending into the reserve crown and with some appearing more like a midline sagittal fracture (**Figure 4**).

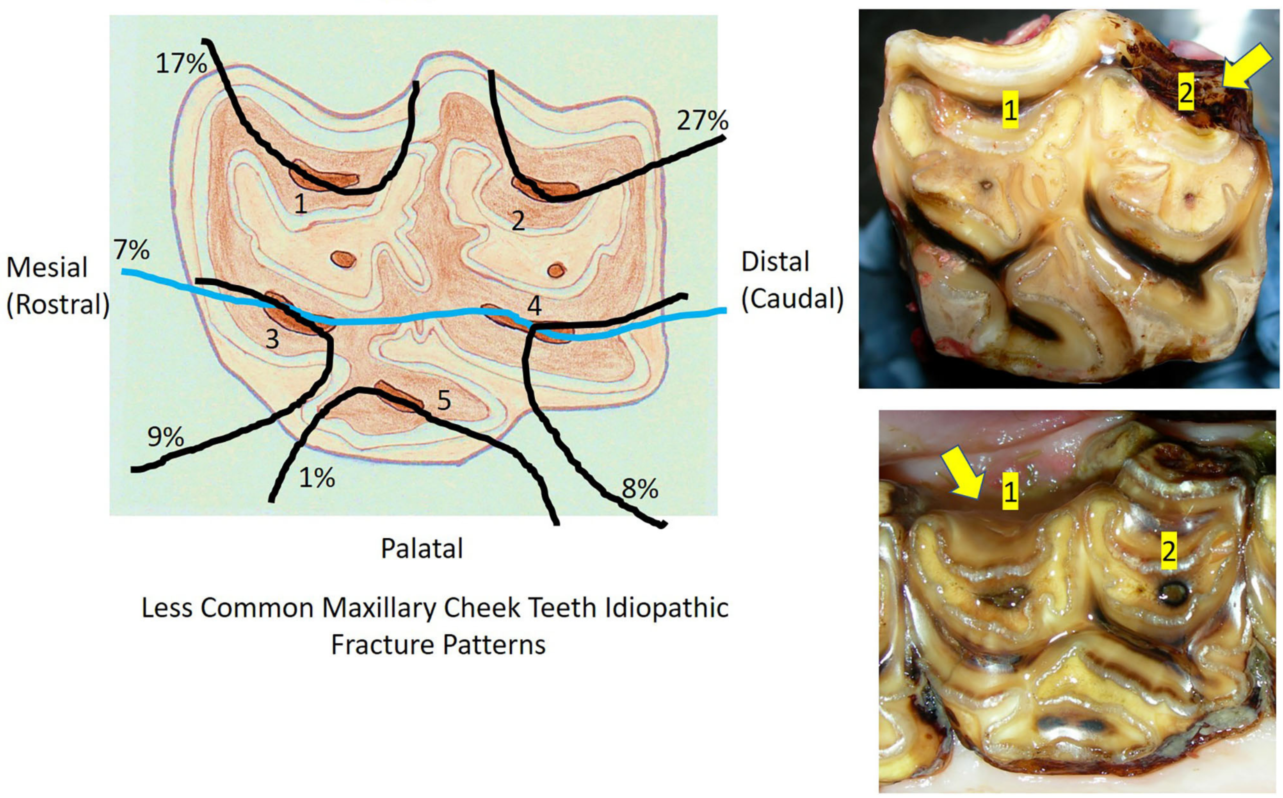


**FIGURE 3 |** The diagram on the left shows the six most common idiopathic maxillary cheek teeth fracture planes other than "slab" fractures (i.e., "atypical fractures") and the proportions of each fracture plane in this category, with five patterns involving single pulp horns. The top right image shows a tooth with a second pulp horn fracture and the bottom right image shows a tooth with a first pulp horn fracture.

### Miscellaneous Other ("Atypical") Mandibular Cheek Teeth Fractures

Sixteen other fracture patterns were identified in 62 mandibular cheek teeth. A single pulp horn fracture was present in 38 teeth involving pulp horn 1 ($n = 11$; 18% of the 62 fractures), pulp horn 2 ($n = 10$; 16%), pulp horn 3 ($n = 5$; 8%), pulp horn 4 ($n = 6$; 10%), and pulp horn 5 ($n = 6$; 10%). Two pulp horns were fractured in 10 teeth in seven different patterns, three pulp horns in 12 teeth in three different patterns (most commonly of pulps 3, 4, and 5: $n = 9$; 15%), and four pulp horns were fractured in 2 teeth in the same pattern (**Figure 5**).

### Complete Loss of Maxillary or Mandibular Clinical Crowns

Fractures resulting in complete loss of clinical crown were present in 29 teeth, including 23 maxillary and 6 mandibular teeth. It was not possible to determine the previous fracture patterns prior to complete clinical crown loss in these teeth.

### Age of Affected Horses

The mean, median, and range of ages of horses with different fracture patterns are presented in **Table 1** with accurate data available for 286/300 horses. The median age of affected horses were in general similar (i.e., early in their second decade) and ranged from 11 years (maxillary "slab" pattern) to 15 years (infundibular caries-related fractures). Horses with infundibular caries-related fractures were significantly older ($P < 0.001$) than those with maxillary slab fractures. No other significant differences in ages were observed between groups.

## Triadan Position of Fractured Teeth

### Maxillary Teeth

Most 374/486 (77%) fractures were in maxillary cheek teeth and the maxillary 09 position was preferentially affected, comprising 153/374 (41%) of all fractured maxillary teeth (**Figure 6**). These included 48/88 (55%) of infundibular caries-related fractures, with 19/88 (22%) of this fracture pattern in the Triadan 10 position, but none in the 11 position (**Figure 6**). The frequency of infundibular caries-related fractures differed significantly ($P < 0.001$) between tooth positions, with Triadan 09s significantly ($P < 0.001$) more (OR = 1.107, 95% CI = 1.06–1.19) likely to have this fracture than all other maxillary teeth combined.

Most (145/171; 85%) maxillary "slab" fractures occurred in the Triadan 08–10 positions, with the highest frequency (57/171; 33%) in the Triadan 10s. The original fracture pattern(s) in maxillary cheek teeth with complete loss of clinical crown is

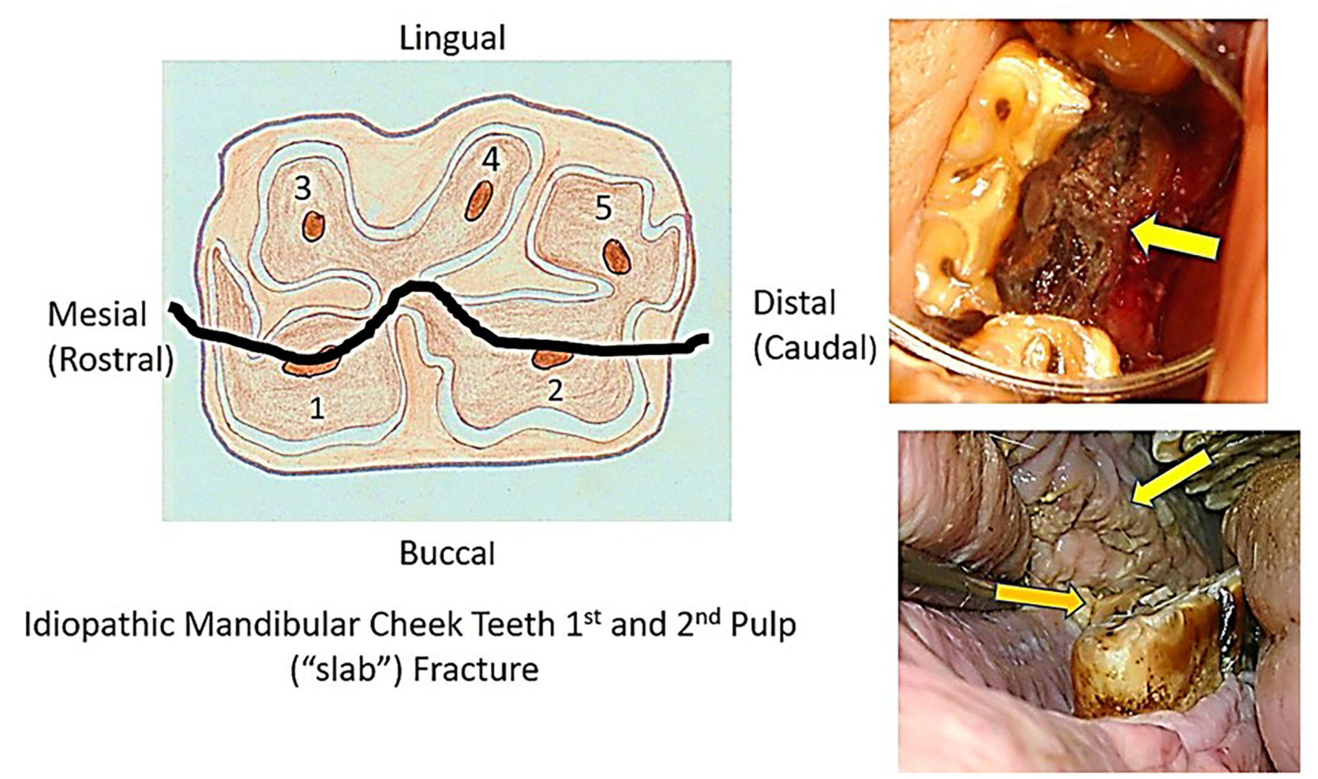


**FIGURE 4 |** The diagram on the left shows the mandibular cheek teeth pulp horn positions and the site of a fracture plane through pulp horns 1 and 2 ("slab" fracture). The top right image shows a left mandibular cheek tooth with a first and second pulp horn fracture and loss of the buccal fragment (arrow) and slight lingual displacement of the remaining tooth. The bottom right image shows a displaced buccal fragment of a "slab" fracture (bottom arrow) that has caused marked, chronic buccal trauma (top arrow).

unknown. Although 16/23 (70%) of this fracture pattern were Triadan 09s, these are unlikely to have been originally caused by infundibular caries-related fractures, because these teeth did not have the full-depth, midline sagittal fractures characteristic of this disorder.

Overall, in all three types of "idiopathic" maxillary fractures ("slab", "atypical," or complete clinical crown loss) ($n = 286$), the Triadan 09s (37% of fractures), Triadan 10s (30%), and Triadan 08s (19%) were significantly ($P < 0.001$) more (OR = 1.12, 95% CI = 1.09–1.18) commonly affected than other three Triadan positions (**Figure 6**).

### Mandibular Cheek Teeth

The frequency of idiopathic mandibular cheek teeth fractures varied significantly between tooth position ($P < 0.001$). The mandibular Triadan 08 and 09s were most commonly affected and comprised 71/112 (63%) of all mandibular dental fractures, with a reduced frequency in the 07 and 10s and the 06 and 11s rarely (5%) affected (**Figure 7**).

## Clinical Signs

No clinical signs were noted in horses with 232/486 (47.7%) fractured teeth (**Figure 8**). Oral pain with dysmastication and quidding was the most common sign in the remainder and was recorded in horses with 126/486 (25.9%) of all fractured teeth. Bitting problems were present in horses with 26/486 (5.3%) fractured teeth. As noted, signs of quidding and bitting problems were combined as "oral pain" for statistical analysis. Atypical mandibular cheek teeth fractures were significantly ($P < 0.001$) more likely (OR = 3.31, 95% CI = 1.91–5.76) to be associated with oral pain and bitting problems (observed in 32/62 = 51.6%) than all other fracture types combined (105/42 = 24.8%). Fractures with complete clinical crown loss were associated with the lowest frequency (10%) of oral pain (**Figure 8**).

Unilateral nasal discharge was present with 88/374 (23.5%) of all fractured maxillary teeth and was significantly ($P = 0.019$) more common (OR = 1.9, 95% CI = 1.1–3.2) with infundibular caries-related fractures (28/88 = 31.8%) than with all other types of maxillary teeth fractures (combined 60/284 = 21.1%).

Maxillary ($n = 20$) or mandibular ($n = 13$) swellings were present with 33/486 (6.8%) of fractures (**Figure 8**). Clinical signs of apical infection were determined by the presence of ipsilateral unilateral nasal discharge (due to sinusitis in 86 horses and nasal infection in two cases—with 06/07 fractures) and/or the presence of maxillary or mandibular swellings caused by apical infection. Eight horses had both maxillary swellings and nasal discharge. Overall, clinical signs of apical infection were present in horses with 113/486 (23.3%) fractured teeth, varying from 4/62 (6.5%)

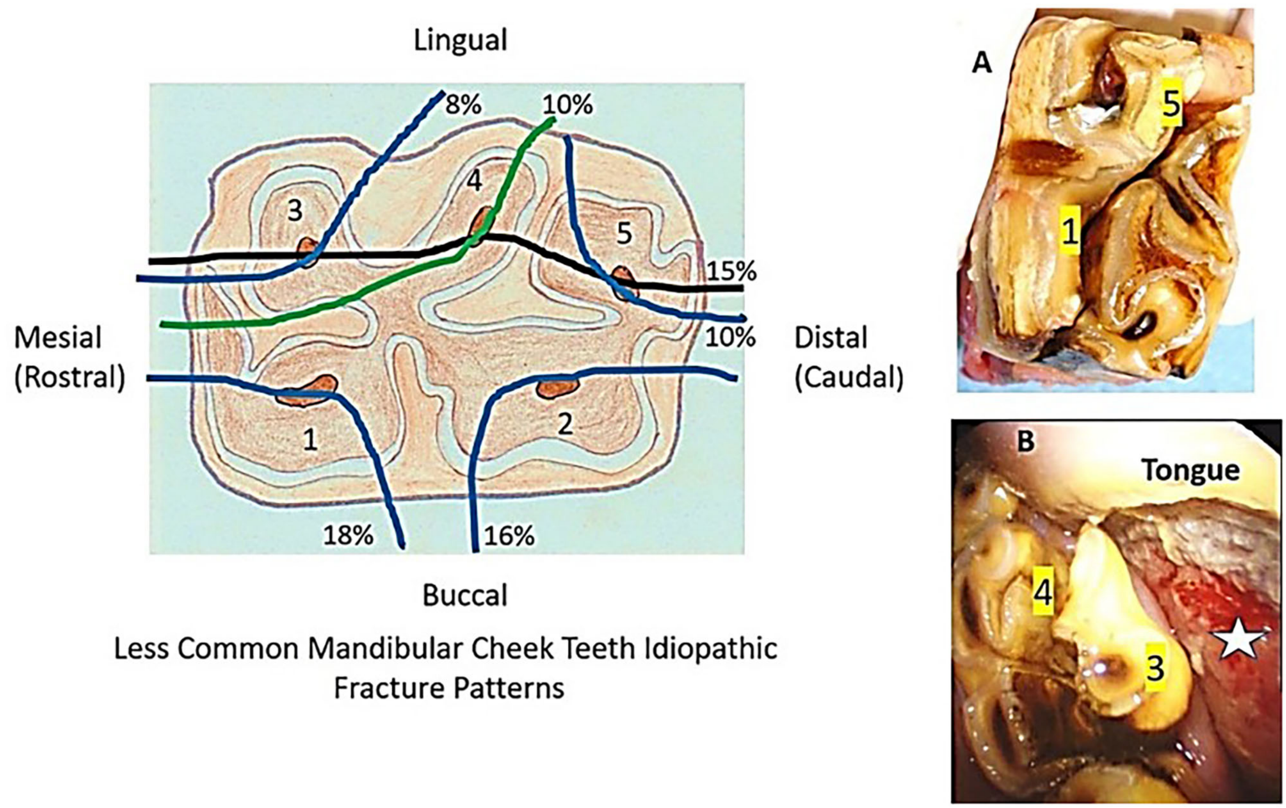


**FIGURE 5 |** The diagram on the left shows the six most common idiopathic mandibular cheek teeth fracture planes (five through single pulp horns) other than slab fractures (i.e., "atypical fractures") and the proportions of each fracture plane in this category. The top right image **(A)** shows an extracted tooth with a fracture extending through the first and fifth pulp horns. The bottom right image **(B)** is an intra-oral view of an oblique fracture through the fourth pulp horn (similar to that shown in the diagram on the left). The smaller displaced fragment (containing the third pulp horn) remains attached by its periodontal and gingival attachments and has caused severe tongue ulceration (star).

**TABLE 1 |** The mean, median, and range of ages (in years) for horses with six different cheek teeth fracture patterns.

| Age (years) | Infun caries | Max slab | Atypic max | Man slab | Atypic man | No clin crown |
|---|---|---|---|---|---|---|
| No of teeth | 88 | 171 | 92 | 44 | 62 | 29 |
| Mean (sd) | 14.1 (3.83) | 11.9 (4.21) | 13.5 (4.86) | 13.2 (4.53) | 13.2 (5.32) | 12.8 (4.45) |
| Median | 15 | 11 | 13 | 13 | 13 | 12.5 |
| Range | 4–26 | 2–25 | 4–27 | 6–22 | 3–28 | 6–20 |

*Infun caries, infundibular caries-related fracture; Max slab, maxillary first and second pulp horn fractures; Atypic max, atypical maxillary cheek teeth fracture patterns; Man slab, mandibular first and second pulp horn fractures; Atypic man, atypical mandibular cheek teeth fracture patterns; No Clin Crown, fracture with the absence of clinical crown.*

teeth with atypical mandibular fractures to 32/88 (36.4%) teeth with caries-related infundibular fractures. Less common signs were weight loss in 13/486 (3%), headshaking with 6/486 (1.2%), and halitosis with 5/486 (1%) of fractured teeth.

## Treatment of Fractured Teeth

Treatment included extraction of 194/486 (40.0%) fractured teeth, or of all remaining fragments (**Figure 9**). Indications for complete extraction were teeth causing clinical apical infection, or where all remaining fragments were loose on manipulation with extraction forceps or grossly carious. Exodontia was by oral extraction in 138/194 (71%), including by the use of specialized dental picks when insufficient or no clinical crown remained. When oral extraction was not possible, Steinmann pin repulsion ($n = 12$) was used (especially in mandibular teeth with ventral drainage tracts) but later was largely superseded by the minimally invasive transbuccal technique (MITT) ($n = 44$).

Frequency of extractions differed significantly between fracture types ($P < 0.001$), with infundibular caries-related fractures extracted significantly more frequently (81/88; 92%) than all other types. In only 7/88 (8%) of infundibular caries-related fractures were a (single) stable fragment was left *in situ* in horses without clinical signs.

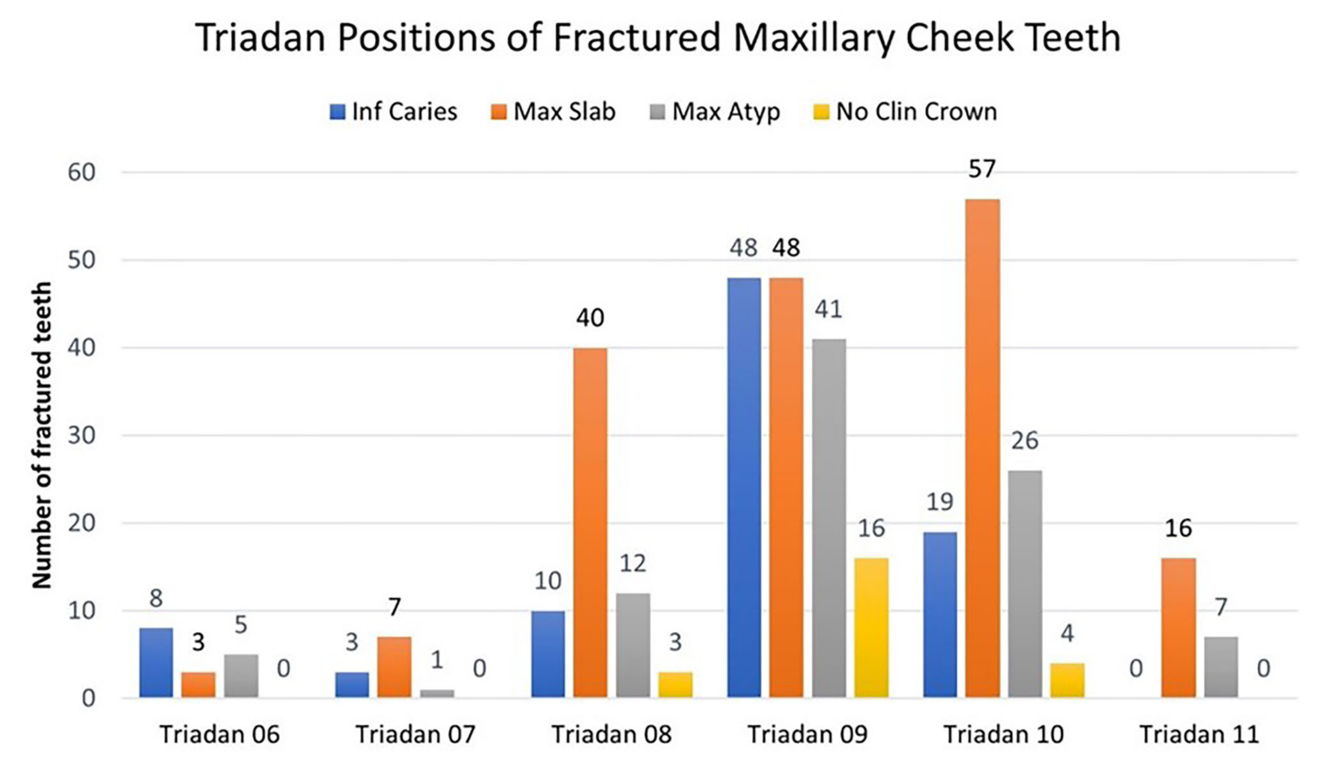


**FIGURE 6 |** Triadan positions of 374 fractured maxillary cheek teeth with four different fracture patterns according to Triadan positions. Inf Caries, infundibular caries-related fracture; Max Slab, maxillary first and second pulp horn fractures; Max Atyp, atypical maxillary cheek teeth fracture patterns; No Clin Crown, fracture with the absence of clinical crown.

A conservative approach was taken for fractured teeth that were not causing clinical signs, including some teeth that later developed occlusal exposure of one or more of the remaining pulps. Conservative treatment included odontoplasty of sharp edges and of possible protruding aspects of the two adjacent (normal) teeth and of a few millimeters of the occlusal aspects of the fractured and of the opposite tooth. Over the period of this study, 3/127 conservatively treated maxillary "slab" fractures subsequently needed exodontia at this clinic due to development of clinical apical infection.

## Case Study of a Horse With Multiple Idiopathic Cheek Teeth Fractures

One horse, which was 7 years old at initial presentation, with multiple cheek teeth fractures, was examined 25 times over a 13-year period (including during the 8 years of this study). Over this time, the horse developed six maxillary and one mandibular idiopathic cheek teeth fractures, including five maxillary "slab" fractures, one initially presenting as a second pulp fracture later extending to the first pulp, one maxillary third and fourth pulp fracture, and one mandibular "slab" fracture. Over this period, clinical signs indicating possible dental disease were recognized in only five occasions. These included nasal discharge due to sinusitis, surprisingly with no dental involvement.

Sudden-onset oral pain/quidding for 1–2 days occurred on four occasions after maxillary buccal "slab" fractures developed and became displaced. These caused buccal trauma that immediately resolved following spontaneous loss or removal of these fragments and odontoplasty. The initial development of fractures caused recognized clinical signs with only one of the seven fractured teeth. The clinical signs on the other three occasions were caused by the development of new maxillary "slab" fractures some 5–8 years after recognition of the original fractures, following further clinical crown eruption. All seven teeth were treated by loose fragment removal and odontoplasty only.

Four of these seven teeth developed occlusal pulpar exposure and one later developed additional fracture patterns, but all four remained without signs of apical infection between 6 and 11 years at the last examination. Three other fractured teeth were of normal appearance, 9–11 years after their initial development of fractures.

## DISCUSSION

Some earlier veterinary literature has descriptions of equine teeth affected with idiopathic and infundibular caries-related fractures, some of which were attributed to the presence of small stones in feedstuffs (9, 11). Dacre et al. (2) first described the

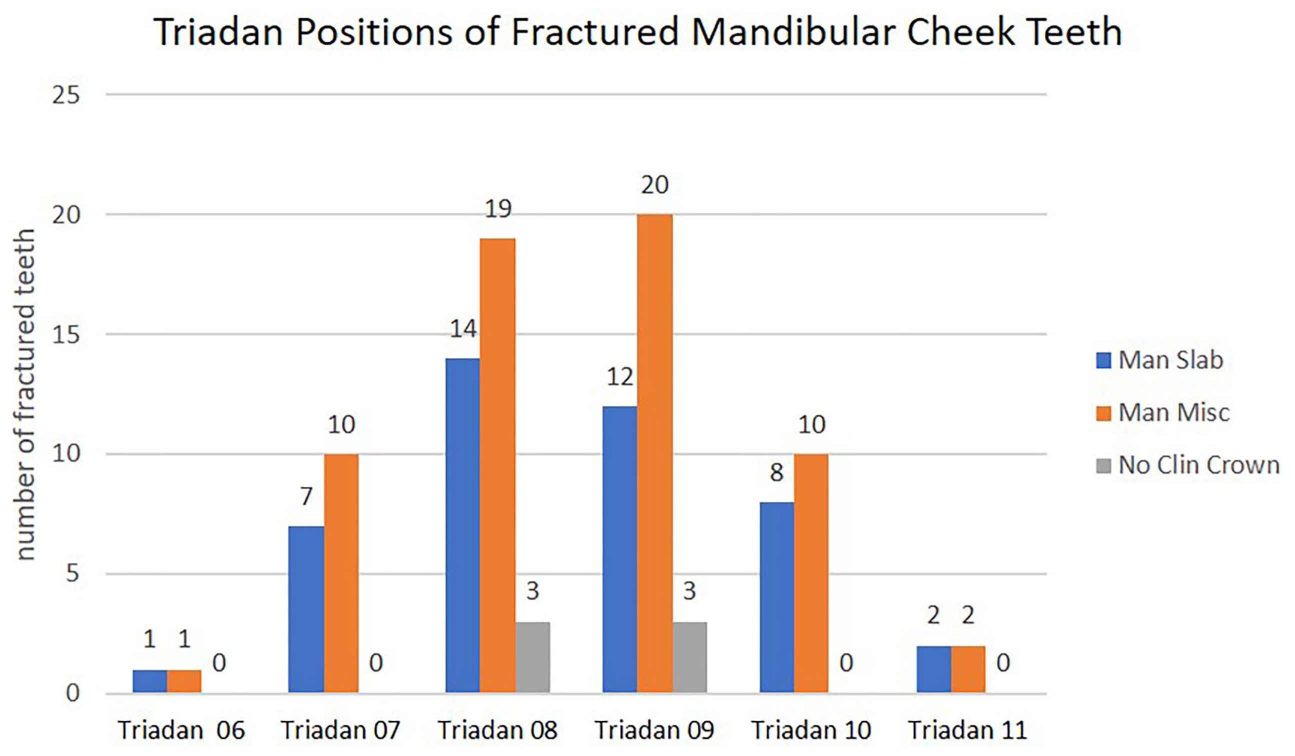


**FIGURE 7 |** Triadan positions of 112 fractured mandibular cheek teeth with three different fracture patterns according to Triadan positions. Man Slab, mandibular first and second pulp horn fractures; Man Misc, atypical mandibular cheek teeth fracture patterns; No Clin Crown, fracture with the absence of clinical crown.

presence of fractures through pulp horns that were present in 86% of idiopathic cheek teeth fractures. They showed chronic, pre-existing endodontic disease in 25% of these teeth that likely predisposed to fractures. Fractures through infundibula were found in the remaining 14% of teeth (2). As noted, this midline sagittal fracture pattern now has an identified etiology and can no longer be termed "idiopathic" and has been termed infundibular caries-related fracture (8).

## Number of Fractured Teeth per Horse

This study found a mean of 1.6 fractured teeth per affected horse, while previous referral hospital (3) and general practice (4) surveys in 2007 found 1.1 and 1.2 fractured teeth per horse, respectively. The increased prevalence in the current study is likely due to improved recognition of this disorder as well as to the increased use of oral endoscopy.

## Maxillary Teeth Fracture Patterns

Maxillary cheek teeth were most commonly (77%) fractured in this study (**Figure 6**), which is similar to previous findings of 82% (1), 60% (2), 82% (3), and 58% (4) maxillary involvement. Caries-related infundibular fractures comprised 23.5% of maxillary dental fractures in this study, similar to the findings of previous referral and general practice studies (both 23%) (3, 4).

The most common maxillary (and overall) dental fracture pattern found in this study was a "slab" (first and second pulp horns) fracture that comprised 46% of all maxillary dental fractures. This was also the most common maxillary dental fracture pattern reported in a pathological study (comprised 43% of maxillary fractures) (2), referral hospital study (45%) (3), and general practice study (48%) (4).

Twenty-eight other patterns of maxillary cheek teeth fractures were found in 92 teeth, i.e., "atypical" fracture patterns, including the six shown in **Figure 3**. These fracture planes traversed single pulp horns in 63% of these "atypical" fractures. The first pulp horns were involved (alone or with other pulps or infundibula) in 46% of "atypical" fractures and the second pulp horn in 50%, as compared to a mean of 31% involvement of the three palatal (third to fifth) maxillary pulp horns. Of interest is that 8.7% (8/92) of these atypical maxillary fractures had a fracture plane running through a single infundibulum in addition to one or more pulp horns. There was evidence of progression of individual first or second pulp horn ("atypical") fractures to become conjoined first and second pulp horn ("slab") fractures in some teeth.

## Mandibular Teeth Fracture Patterns

The most common mandibular cheek teeth fracture pattern (comprising 42% of mandibular dental fractures) was also a first and second pulp horn ("slab") fracture (**Figure 4**), which is a slightly lower proportion than found in a previous referral (57%) (3) or a general practice (53%) (4) study. Most equine fissure (hairline) cheek teeth fractures are transversely oriented (in a bucco-palatal/lingual direction) and seldom cause clinical

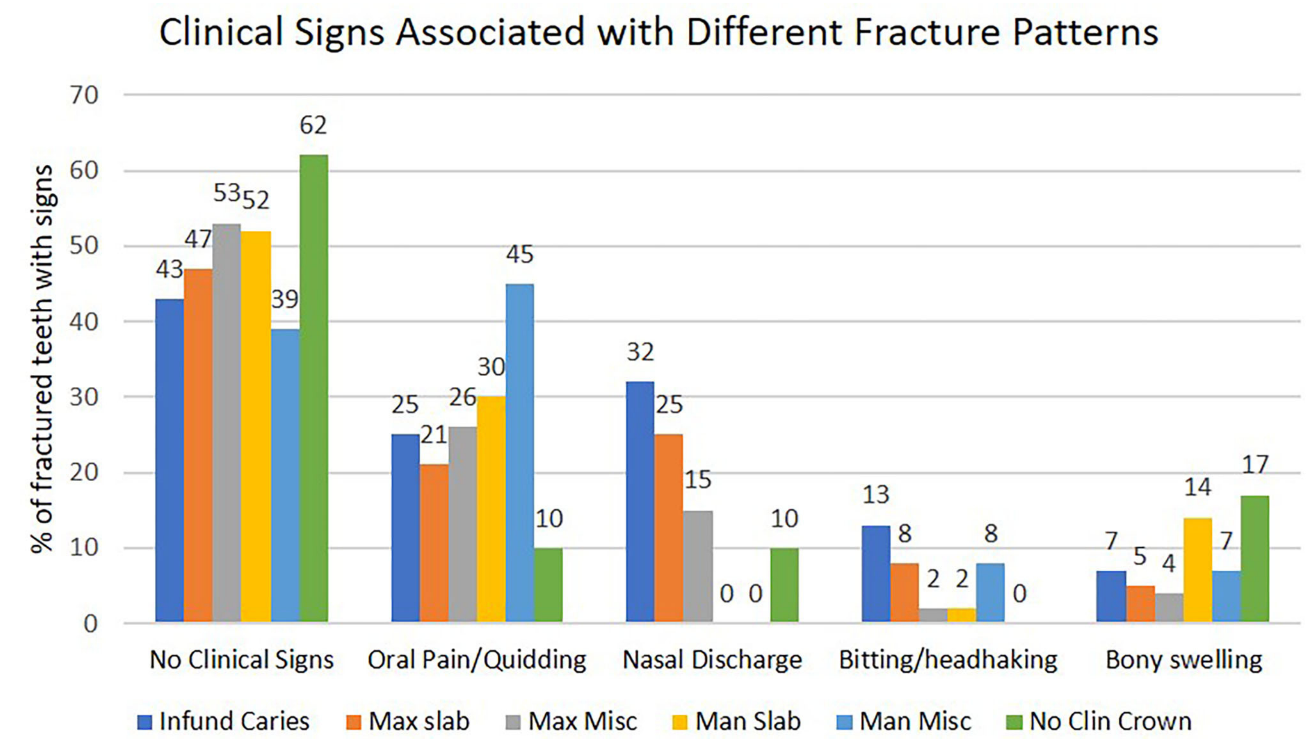


**FIGURE 8 |** The presenting clinical signs in 300 horses with 486 cheek teeth fractures, subdivided into six different fracture patterns. Infund Caries, infundibular caries-related fracture; Max slab, maxillary first and second pulp horn fractures; Max Misc, atypical maxillary cheek teeth fracture patterns; No Clin Crown, fracture with the absence of clinical crown; Man Slab, mandibular first and second pulp horn fractures; Man Misc, atypical mandibular cheek teeth fracture patterns.

disease (12–14). However, two studies have shown that sagittal fissure fractures involving both first and second pulp horns can later cause complete (complicated) first and second pulp horn fractures (15, 16). Pollaris et al. (17) have shown progression of fissure fractures to complete but non-complicated fractures, but Wellman and Dixon (18) have shown pulpar exposure and infection with deep fissure fractures. Sixteen other "atypical" mandibular cheek tooth fracture patterns involving 62 teeth were also described in this study (**Figure 5**), with 61% through a single pulp horn.

## Complete Clinical Crown Loss

Twenty-nine teeth with complete loss of clinical crown, some with caries of the remaining reserve crown, were also identified in this study. Many involved the maxillary 09s, but none as noted had deep sagittal fractures and, thus, were unlikely to have been originally caused by caries-related infundibular fractures. In retrospect, this fracture pattern could possibly have been included in the "atypical" fracture group.

## Age of Affected Horses

Horses with infundibular caries-related fractures (median 15 years of age) were significantly older than horses with maxillary slab fractures (median 11 years). A similar age differential (median ages of 12 vs. 10 years) was found in a previous study but was not statistically significant, possibly due to low numbers of cases (3). The age of horses with infundibular caries-related fractures is likely related to when infundibular cemental defects in these teeth (many of which are located deep in the infundibulum) become occlusally exposed and develop infundibular caries (5–7, 19).

However, the reason for the relatively mature age of horses with idiopathic fracture patterns (mean 11.9–13.5 years) dependent on the fracture pattern is unclear. In idiopathic fractured teeth with pre-existing endodontic disease (2), it may be due to the slow progression of this disease that prevents deposition of new secondary circumpulpar dentine and also gradually weakens the integrity of dentine. In most (other) teeth without pre-existing endodontic disease, it would seem more logical that such fractures should develop in much younger teeth that have less secondary dentine and thus larger pulp horns than in mature teeth, such as what was found in this study (median age 11–13 years for "idiopathic" fractures).

## Triadan Position of Fractured Teeth

The maxillary 09s were the most commonly fractured tooth position (comprised 41% of all maxillary dental fractures). This can be partly explained by the recognized predisposition of Triadan 09s to develop infundibular caries-related fractures (5–7, 15, 19). In this study, 55% of this fracture pattern was in the 09 position. However, the 09s as well as the 08s and the 10s were also commonly affected with all other types of maxillary

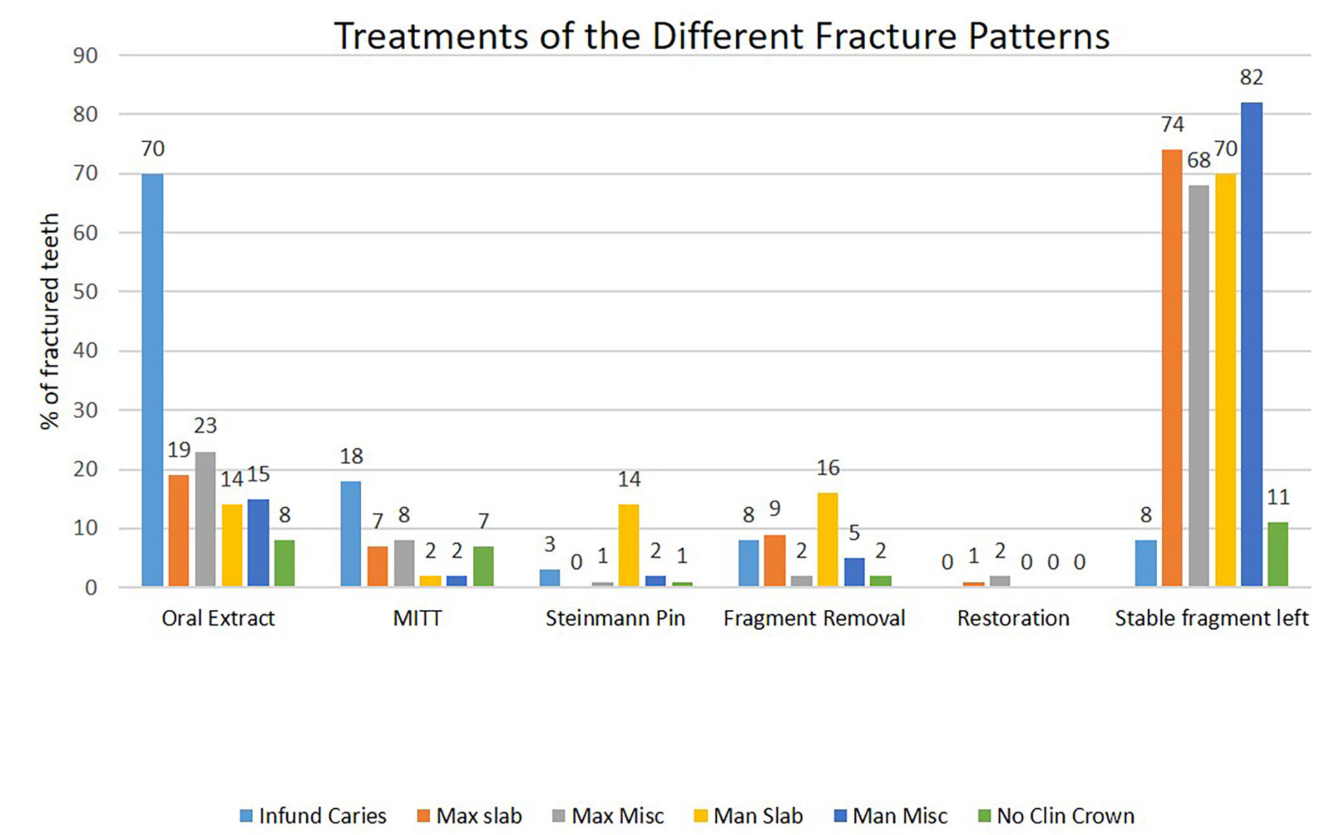


**FIGURE 9 |** Treatments of 486 fractured cheek teeth with six different fracture patterns: including oral extraction (Oral Extract), minimally invasive transbuccal technique (MITT), Steinmann pin repulsion (Steinmann pin), fragment removal, dental restoration (Restoration), or stable fragment left *in situ*. Infund caries, infundibular caries-related fracture; Max slab, maxillary first and second pulp horn fractures; Atypic max, atypical maxillary cheek teeth fracture patterns; Man slab, mandibular first and second pulp horn fractures; Atypic man, atypical mandibular cheek teeth fracture patterns; No Clin Crown, fracture with the absence of clinical crown.

dental fractures (**Figure 6**) as previously found (2–4, 8). The other, more peripheral Triadan positions including the Triadan 11s were uncommonly fractured, despite the highest occlusal pressures being in the teeth closest to the temporo-mandibular joint, i.e., the 11s (20).

Most mandibular cheek teeth fractures involved the two most centrally located teeth (08s and 09s) as previously reported (3, 4). There was a decreasing prevalence of fractures toward the peripherally situated teeth, and fractures were rarely found in the 06 and 11s (2 and 4%, respectively, of all mandibular teeth fractures) (**Figure 7**). Both studies also seldom found mandibular Triadan 10 fractures (3, 4).

## Clinical Signs

No clinical signs were noted in horses with 48% of fractured teeth. This high proportion without signs may reflect current better recognition of these disorders and improved diagnostic techniques. In contrast, an earlier study found that every fractured tooth caused clinical signs, including apical infections in 50% of cases (1). Oral pain with dysmastication and quidding was the most common recognized sign in this study (associated with 26% of fractures) and was most common in horses with "atypical" mandibular fractures (45% incidence). Oral pain/quidding was least common (10%) with fractures with total loss of the clinical crown—which therefore could not lacerate the soft tissues. This fracture pattern also had minimal masticatory-induced movement of the remaining crown that could overstretch the periodontal ligaments. Bitting and headshaking problems, also likely due to oral discomfort, were present in 7% of cases, which is inexplicably much lower than previous referral (28% incidence) (3) and practice (29%) (4) studies.

Signs of apical infection as determined by nasal discharge or swelling of the supporting bones was present with 23% of dental fractures. It was more common with infundibular caries-related fractures (36% incidence) and maxillary slab fractures (27%) and lowest with mandibular "slab" (14%) and "atypical" mandibular (7%) dental fractures. These findings are similar to a referral hospital study that found 21% of fractured teeth to have clinical apical infection (3) and, as expected, much greater than a general practice survey that found just 3% of fractures to have clinical apical infection (4). However, the findings of these three studies differ greatly from a recent CT study by Rowley et al. (10) that showed 77% (62/81) of all fractured cheek teeth, including 80% of maxillary cheek teeth and 43% of mandibular cheek teeth, have CT evidence of apical infection. In that study, all infundibular caries-related fractures and 73% of maxillary "slab" fractures had apical changes. These findings would suggest that a high proportion of asymptomatic fractured teeth in the current study also had apical infection that were confined to the alveolus or did not necessarily cause generalized pulpar death.

### Treatments

All teeth causing clinical apical infection (i.e., nasal discharge, sinus tracts, or gross bony swellings) or where all dental fragments were loose or very carious were extracted. Exodontia was *per os* with forceps and picks where possible. Teeth with infundibular caries-related fractures had the highest level of clinical apical infection, and thus, 92% (81/88) of such teeth were extracted. If MITT had been available earlier in this study, four of the seven cases where dental fragments were left would likely have had all fragments extracted. Lower proportions of teeth with other fracture patterns met the above criteria for extraction and so fewer were extracted.

There is no consensus regarding the treatment of fractured teeth that are not causing clinical signs. A conservative approach to treatment was adopted in this, as in a previous referral hospital study (3). Thus, larger stable dental fragments (e.g., 74% of maxillary cheek teeth with loss of "slab" fractures) were left *in situ*. It was hoped that any exposed viable pulps would become sealed off with tertiary dentine or, alternatively, that any possible pulpar and apical infection of the remaining tooth would be walled off within a sclerotic alveolus and prevent clinical signs of apical infection from developing.

At least 3/171 (2%) conservatively treated maxillary teeth with "slab" fractures later developed clinical apical infection and required exodontia at this clinic. It is possible that other conservatively treated horses later developed such signs and were treated elsewhere.

A smaller referral study found a higher proportion of 6/22 (27%) of conservatively treated fractured teeth to later require exodontia (3).

In the current study, some conservatively treated fractured teeth later developed occlusal exposure of the remaining pulp horns indicating death of these pulp horns (and thus of the tooth) without clinical signs of apical infection. There is increased rationale for the extraction of such teeth, or at least monitoring them by imaging. However, as noted, a CT study found that 77% of fractured teeth have imaging evidence of apical infection, although not necessarily confirmative of pulpar death (10). The rationale for extraction of such a high proportion of fractured teeth (e.g., one horse in this study with 10 fractured teeth) would not have been justified. The endodontic treatment of equine cheek teeth has been recently reported (21) and will likely be increasingly used in the future. However, there is difficulty in gaining suitable access to the most common idiopathic fracture pattern (i.e., maxillary "slab" fractures) that would likely benefit from endodontic treatment, but some clinicians have overcome this technical problem (Lundström, 2018, personal communication).

Extractions of multiple fractured teeth, such as maxillary slab fractures (often Triadan 10s), in young mature horses can be technically difficult, with further extraction-related fractures occurring. In fact, postextraction sequelae may result in protracted clinical disease in horses without previous clinical signs. Conservative treatments, such as those performed on one horse with seven fractured teeth and examined 25 times over 13 years, were found to be satisfactory for that horse's welfare and for that client's expectations. Extraction of all seven fractured teeth would have been far more traumatic for this horse and also would have reduced its ability to masticate effectively.

There may also be financial incentives to extract teeth that have endodontic or apical changes. The annual renewal of a horse's veterinary care insurance may place pressure for dental extraction prior to the renewal date, in case dental fractures are excluded in future policies. Perhaps, equine health insurers need to take a longer term (and possibly less expensive) view on such cases that will also be in the horse's welfare interests.

## CONCLUSIONS

Non-traumatic cheek teeth fractures are increasingly recognized in horses, with almost half of the fractures in this study in horses with no clinical signs. Fractured teeth with apical infection (which includes most teeth with infundibular caries-related fractures) and those with multiple fractures or advanced caries require extraction. Most other teeth do not necessarily need immediate extraction, and most can remain *in situ* for many years without causing clinical signs, despite the presence of subclinical endodontic and apical changes in some. Further studies of these disorders with repeat imaging and obtaining long-term follow-up information of all cases would be of value.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

PD contributed to study design and execution, data analysis and interpretation, and manuscript preparation. RK contributed to study execution and manuscript preparation. RR contributed to data analysis and interpretation, and manuscript preparation. All the authors approved the final manuscript.

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# Diagnosis and Surgical Treatment of Idiopathic Primary Sino-Nasal Obstruction in Miniature Horse Breeds: Long-Term Follow-Up of Seven Cases

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Idiopathic sino-nasal obstruction resulting in retention of large amounts of liquid in the paranasal sinus compartments was diagnosed in seven young (2. 2 ± 0.7 years) miniature-breed horses based on clinical, endoscopic, radiographic, and CT scan examinations. The most prevalent clinical signs included decreased or no airflow from the nostril(s) (7/7) and nasal discharge (6/7). The problem presented bilaterally in six of seven cases. An alternative sino-nasal communication was created through bone flap osteotomy surgery and perforation of the ventromedial floor of the dorsal conchae in all cases, followed by fixation of silicone irrigation tubes/Foley catheters in six of seven cases to keep the newly created ostium patent. This resulted in long-term resolution of the problem with good cosmetic appearance in all animals following a median period of 19 months. Premature loss of fixed tubes was reported in three cases.

**Keywords: bilateral sinus disease, single caudally based front-nasal bone flap, miniature horse breed, idiopathic sino-nasal obstruction, idiopathic sinus pathology**

## INTRODUCTION

A variety of sino-nasal pathological conditions in horses have been well-described. Common diseases include primary and secondary sinusitis (1–3), paranasal sinus cysts (4), progressive ethmoid hematoma (5, 6), and more rarely encountered sinus neoplasia (7, 8). A correct diagnosis is straightforward in the majority of cases and based on the patient's medical history, clinical symptoms, and the results of further diagnostic procedures such as endoscopy, radiography, computed tomography (CT), sinoscopy, and bacteriological and/or histological analysis of pre-operative retrieved fluid and tissue samples, respectively. Primary sinusitis can respond well to systemic treatment with broad-spectrum antibiotics. Other pathologies often require surgical interventions such as transnasal sinus approaches or external trephination, sinoscopy, or sinusotomy to restore nasomaxillary mucus drainage or to deal with the encountered pathology.

A seldomly reported sinus pathology in horses is sinus mucocele. Mucoceles are believed to develop following obstruction of the nasomaxillary aperture between sinus and the nasal cavity. Progressive deformation of the surrounding structures is the result of continuous production and accumulation of mucus in the isolated sinus compartments. In humans, the most common causes of occlusion of sinus drainage toward the nose are chronic infection, allergic sino-nasal disease, trauma, and previous surgery (9, 10). In equine veterinary literature, this pathology has not been reported in some larger retrospective case series (3, 11). One older case report briefly mentions mucocele sinusitis in a thoroughbred filly resolved by simple trephination, flushing, and antimicrobial treatment (12). A more recent case report describes the use of a caudally based fronto-nasal bone flap and sino-nasal fenestration to successfully resolve bilateral sinus mucocele in an American miniature horse (13). We describe the clinical symptoms, diagnostic work-up, and long-term follow-up of seven comparable cases of sino-nasal obstruction treated by bone flap surgery and restored drainage toward the nasal cavity.

## MATERIALS AND METHODS

The medical records of six horses presented to the equine services of the Faculty of Veterinary Medicine at Ghent University between January 2011 and January 2018 where a diagnosis of idiopathic sino-nasal obstruction was made were reviewed. In January 2018, an additional call was distributed to EVDC Eq specialists to contribute comparable cases from their case load that added one extra case (WHT) to the study population.

The main criterion that was used to diagnose sino-nasal obstruction included uni- or bilateral accumulation of fluid within sinus compartments in the absence of any other sinus pathology such as sinusitis, paranasal sinus cyst, progressive ethmoid hematoma, or any kind of neoplasia. All horses received a complete clinical examination with special attention to facial deformities in the area of the frontal and maxillary sinus compartments, nasal discharge, and air flow from both nostrils. Nasal endoscopy was performed if possible, *via* both nostrils. The dentition was orally examined for any signs of associated dental disease. Radiographs were acquired using computed radiography systems (Ghent University: Konica Minolta before 2015, Agfa CR30 after 2015, and Agfa DX-M after 2016; B&W Equine Hospital, Siemens Gantry mounted-Agfa CR/Canon-Eklin DR system). Additional computed tomography imaging was performed under general anesthesia in dorsal recumbency (Lightspeed QX/I33, 4-slice helical scanner at Ghent University; Toshiba Aquilon-B, 16-slice helical scanner at B&W Equine Hospital) (120 kVp, 160 mAs, pitch 0.75, slice thickness 1.25–2.5 mm, matrix 512 × 512, scan FOV between 254 and 500 mm, creating bone and soft tissue algorithm reconstructions at Ghent University and at B&W Equine Hospital). In animals in which i.v. jugular vein contrast medium was administered (cases 1–6), a post-contrast acquisition was obtained 2 min after the start of the contrast injection. Contrast medium (Omnipaque, GE Healthcare) at a dosage of 2 ml/kg bodyweight and standardized concentration (iohexol 300 mgI/ml) was administered as a single bolus by use of a power injector.

Surgical exploration was performed using a single caudally based fronto-nasal bone flap as described by Easley and Freeman (13) for cases with bilateral involvement of sinus compartments, or a standard unilateral fronto-nasal bone flap as described by Freeman et al. for unilateral cases (14). Surgery was performed under general anesthesia following induction of anesthesia and orotracheal intubation. Animals were positioned in sternal recumbency to facilitate access to both sides of the head. More recent cases were treated in the standing animal using continuous rate infusion (CRI) of detomidine and regional maxillary nerve blocks (cases 5 and 6) (15). Once the bone flap was elevated, all liquid contents were removed from the sinus compartments by suction followed by copious lavage with Hartmann's. An alternative sino-nasal communication was created by perforating the medio-ventral wall of the rostral aspect of the dorsal conchal sinus by digital pressure or using a blunt tipped instrument. Using a scalpel blade and/or dissection scissors, the hole was enlarged to reach a minimum size of 2 cm. Diffuse bleeding from the conchal wall margins was stopped by temporary pressure using gauze sponges for 5–10 min. Then, a 1.5-cm outer diameter silicone tube (cases 1–6) or 24F Foley catheter (case 7) was introduced to maintain patency of the fistula allowing ongoing drainage. The distal end of each silicone tube was fixed to the ipsilateral nostril with a simple interrupted suture. The Foley catheter remained in position through inflation of the balloon within the sinus. If continuous significant hemorrhage was observed after release of local pressure, the dorsal conchal sinus was packed with gauze bandages for hemostasis and no tube or catheter was introduced. The distal end of the bandage exited through the nasal cavity and was fixed to the nose. The frontal bone flap was replaced, and the periosteum was sutured using a simple continuous pattern with 3M Vicryl Plus (Ethicon). The skin was closed using stainless steel staples (cases 1–6) or simple interrupted sutures through the skin and periosteum using 3.5 M Monosof (Tyco) (case 7). Post-operative irrigation of the sinuses with saline was performed through pre-drilled trephination holes in cases 1–6. A small stab incision was made centered over the ipsilateral concho-frontal sinus compartment followed by drilling a trephination hole with a 3.2-mm bur. The stab incision was closed with two stainless-steel staples. A 16-gauge needle attached to an infusion line and a 1-L bag of sterile saline was passed through the stab incision and the associated trephine hole to allow daily flushing (once or twice a day) for a variable period (cases 1–6). In case 7, the Foley catheters were used to flush the sinus compartments accordingly. Post-operative antimicrobial treatment consisted of intramuscular administration of procaine benzyl penicillin (20,000 IU/kg once daily) for 2–7 days, sometimes continued for another 2 weeks orally with potentiated sulfonamides (25 mg/kg twice daily) based on each patient's individual clinical progression and the surgeon's preference. NSAIDs were administered orally for 3–7 days. If possible, sino-nasal tubes were kept in place for a period of 3 weeks before removal. Owners were advised to box-rest their horses or have them turned out to pasture until removal of sino-nasal tubes.

Owners were contacted by telephone after a minimum time period of 6 months to obtain long-term follow-up information. They were questioned about the recurrence or persistence of symptoms such as abnormal respiratory noise, nasal discharge, and any health problems that might have occurred following the surgical treatment of their horse. They were also asked

**TABLE 1** | Summary data for horses undergoing treatment of idiopathic sino-nasal obstruction.

| Horse No. | Age (years) | Breed | Sex | Duration (weeks) | Uni- or bi-lateral | Radiographic views | CT scan performed | Surgery | Follow-up (months) | Premature loss tube*/Foley** | Recurrence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3 | AM | F | 3 | Bilateral | 4 | Yes | CB-FNBF | 88 | No* | No |
| 2 | 1.7 | S | F | 3 | Bilateral | 4 | Yes | CB-FNBF | 30 | Yes* (right) | No |
| 3 | 3.1 | AM | F | 4 | Bilateral | None | Yes | CB-FNBF | 26 | No* | No |
| 4 | 1.7 | S | F | 3 | Bilateral | None | Yes | CB-FNBF | 19 | No* | No |
| 5 | 2.5 | AM | F | 9 | Right side | 2 | Yes | Right FNBF | 14 | No* | No |
| 6 | 1.4 | S | F | 36 | Bilateral | 4 | No | CB-FNBF | 9 | Yes* (both) | No |
| 7 | Unknown | AM | F | 9 | Bilateral | None | Yes | CB-FNBF | 6 | Yes** (both) | No |

*AM, American miniature horse; S, mini-Shetland pony; F, female; CB-FNBF, caudally based fronto-nasal bone flap. *silicone tube, **Foley catheter.*

for their subjective evaluation of the scar at the level of the surgical incision.

## RESULTS

**Table 1** summarizes individual data of the seven animals. All animals included in the study group were mares. Breed distribution consisted of four American miniature horses and three mini-Shetland ponies with a mean age of 2.2 ± 0.7 years and ranging in weight from 64 to 140 kg. Median duration of symptoms before referral to a specialized center was 4 weeks (range 3–36 weeks). Treatment with antibiotics and NSAIDs was given in five of seven animals for variable periods without any improvement of symptoms. On admission, clinical parameters such as body temperature, heart rate, and CRT were within normal limits. Apparent clinical symptoms are summarized in **Table 2**. Decreased air flow from the nostril(s) was present in all animals although varying in location (uni- or bilateral) and severity. Respiratory rate was elevated in two animals that showed open mouth breathing due to bilateral severe narrowing of nasal passages (cases 1 and 2). This necessitated an emergency tracheotomy in one of them (case 2). The latter horse as well as case 6 produced a snoring expiratory noise. Endoscopy of the upper respiratory tract, performed in six of seven horses (not performed in case 7), confirmed varying degrees of narrowing of nasal passages due to medial displacement of the dorsal concha. In three of six animals (cases 1–3), an 8-mm-diameter flexible endoscope could not be introduced further than 2–3 cm. Nasal discharge was variably unilateral (cases 5 and 6) or bilateral (other cases) and was mucoid without an associated abnormal odor. Two animals with bilateral sinus disease (cases 1 and 4) showed mild, bilateral facial deformity in the region of the frontal bones, which was more pronounced on the right side in case 4. A third animal (case 2) had undergone prior bilateral frontal sinus trephination and flushing, which resulted in unilateral (right) localized wound infection and subsequent edematous swelling in that region. Epiphora was not recorded in any of the animals. Dental examination revealed no oral dental pathology in any patient.

Radiographic images were available for four of seven patients. In all patients, laterolateral and dorsoventral views were performed; in three patients, oblique views were also included (right dorsal to left ventral oblique and left dorsal to right ventral oblique). All four patients demonstrated homogeneous diffuse soft tissue opacification in the normally gas-filled frontal and maxillary sinuses. The single patient with unilateral disease (case 5) had only two views included in the study; the dorsoventral projection clearly demonstrated the soft tissue opacification of the right sinus complex. In only one patient (case 6) was there a mass effect noted with marked left-sided deviation of the nasal septum (**Figure 1**). This patient had bilateral disease; however, this was uncertain based on the radiographic study only.

**TABLE 2** | Clinical signs encountered in seven cases with sino-nasal obstruction in miniature horse breeds.

| Clinical signs | *n* |
|---|---|
| Decreased/no air flow from nostril(s) | 7 |
| Nasal discharge | 6 |
| Deformation frontal bone region | 2 |
| Open mouth breathing | 2 |

A CT study was performed in six of seven patients. In five of six horses, bilateral disease was present, whereas in one patient, the disease was unilateral. In five patients, the affected sinus compartments were almost completely filled with a homogeneous fluid attenuating content. Often a small normal gas attenuating area was only identified at the level of the sphenopalatine sinuses. Hounsfield units (HU) of the fluid-attenuating content varied in five patients from 1 to 25 HU. In case 5, HU were slightly higher and varied from 25 to 35 HU. In another patient (case 2), the sinus compartment was incompletely filled with larger normal gas attenuating areas remaining in the caudal maxillary sinus, frontal sinus, and presence of fluid/gas interfaces in the conchal sinuses. The content was more heterogeneous compared in this case, with dispersed gas attenuating foci within the sinus content. In this patient, trephination osteotomies were present in both the left and right frontal bone. At the level of the right trephination site, there was marked soft tissue swelling present with subcutaneous encapsulated fluid and gas accumulation. There was also a mild to moderate amount of periosteal reaction detected adjacent to the right trephination site. In case 4, there was bony deformation of the skull with focal outward distension of the right frontal

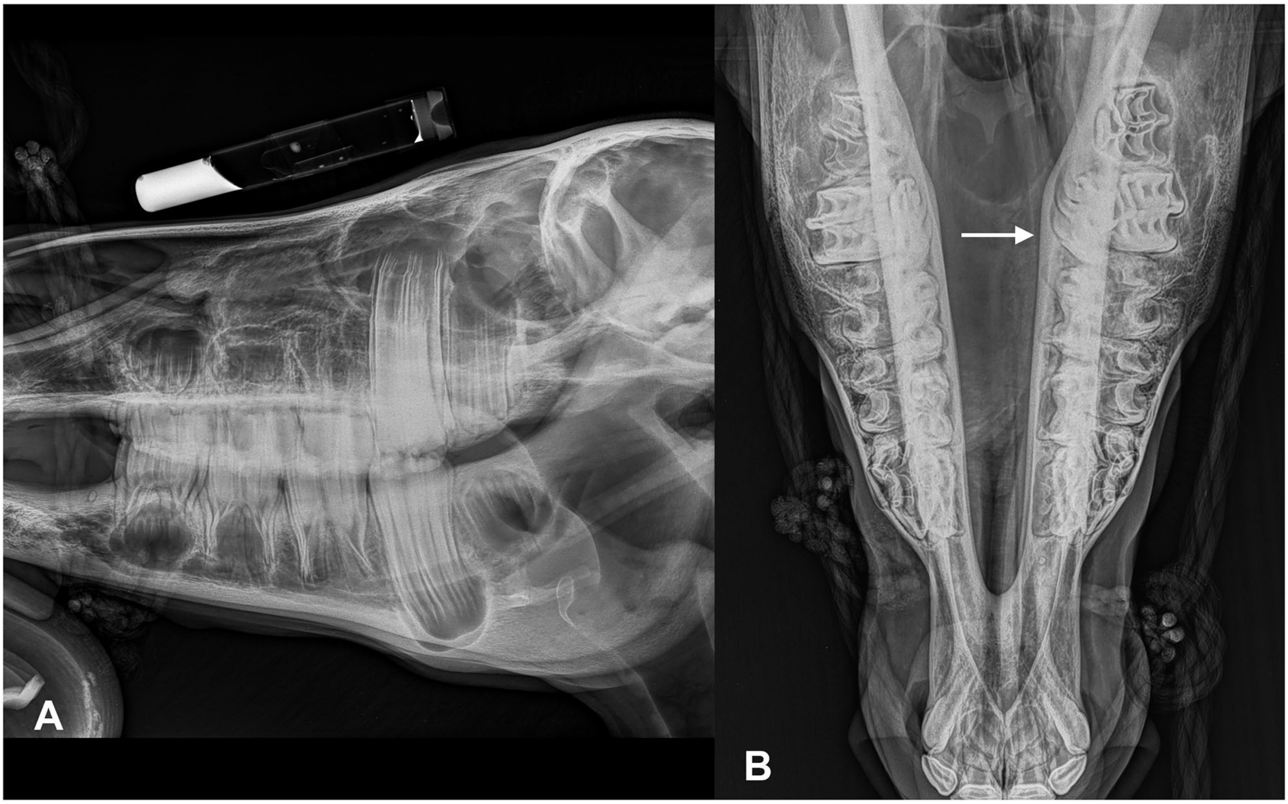


**FIGURE 1 |** Lateral **(A)** and dorsoventral **(B)** (left in the image is right of the patient) radiographic views of mini-Shetland pony (case 6) presented with bilateral disease. Note that the sinus compartments demonstrate a diffuse soft tissue opacification. The nasal septum is severely deviated toward the left side (white arrow).

bone associated with a moderate amount of ill-defined, periosteal reaction, and thinning of the frontal bone. In this patient, there was also marked septal deviation toward the left side (**Figure 2**). This patient did not have a radiographic exam before the CT. In all patients, there was marked distension of the conchal sinuses resulting in narrowing of the nasal passages. Deviation of the nasal septum was noted in five patients, in all cases away from the sinus compartments that were most severely affected. Case 1 did not show deviation of the septum as left and right sinus compartments were equally affected. The dentition showed changes consistent with physiological age-related developmental changes that in miniature breeds can be highly variable between individuals and compared to typical changes of larger breeds. However, specific changes pathognomonic for acquired dental pathology were not recorded.

A post-contrast study was performed in five of six patients (cases 1–5); in none of these was contrast enhancement of the sinus content detected. In three patients (cases 3–5), rim enhancement was noted surrounding the content representing most likely the mucosal lining of the affected sinus compartment (**Figure 3**). In five patients, the medial retropharyngeal lymph nodes were included in the scan. In three of these (cases 2, 3, and 7), mild to moderate lymphadenopathy was present. None of the patients underwent a follow-up CT study.

Subsequent surgical treatment was straightforward in all cases. Five horses (cases 1–4 and 7) were treated under general anesthesia. Horses were given acepromazine (0.03 mg/kg) intramuscularly 30 min prior to surgery. Premedication included romifidine (0.2 mg/kg) and morphine (0.1 mg/kg) intravenously. Induction of anesthesia was done by intravenous injection of ketamine (0.2 mg/kg) and midazolam/diazepam (0.15 mg/kg). Following oro-tracheal intubation in four of five horses, maintenance of anesthesia was done with a mixture of oxygen and isoflurane. The tracheotomy performed pre-operatively in case 2 was used for intubation instead of oro-tracheal intubation. Surgery was performed in the two other horses (cases 5 and 6), conscious and standing under sedation protocols. Intravenous premedication included detomidine (0.01 mg/kg) and methadone (0.5 mg/kg). The appropriate plane of sedation was maintained using a CRI of detomidine (0.01 mg/kg/h). Local analgesia was provided by regional anesthesia with mepivacaine (bilateral maxillary nerve perineural analgesia; subcutaneous infiltration along the surgical incision lines). When opening the sinus compartments, large volumes of mucus exuded and were evacuated using suction. The right concho-frontal and caudal maxillary sinus compartments of case 2 that had prior trephination and flushing were filled with malodorous, purulent liquid contents. Initially, at the time

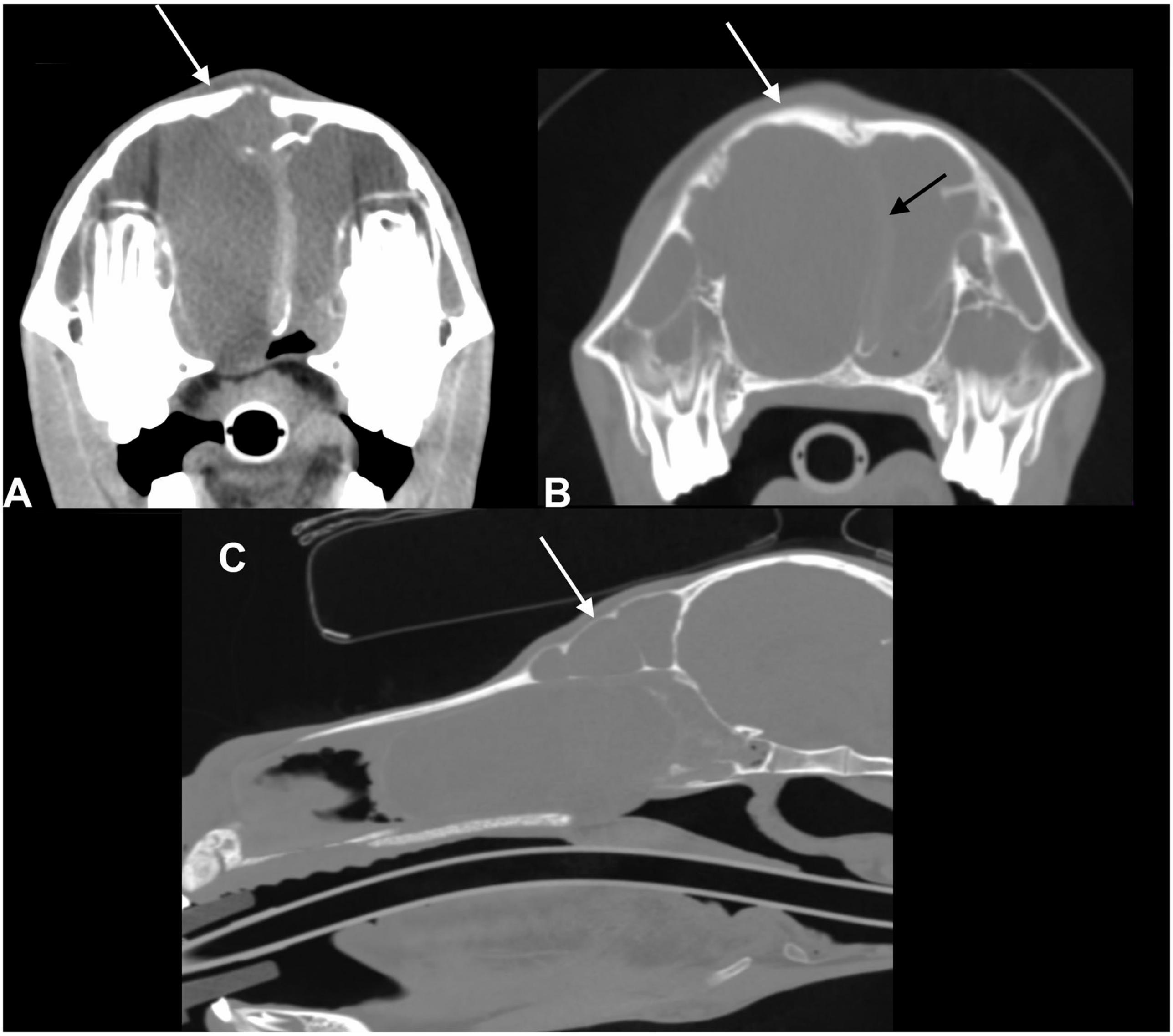


**FIGURE 2 |** Transverse CT images of a mini-Shetland pony with bilateral sinus disease (case 4) processed with soft tissue **(A)** and bone **(B)** filters (left in the image is right of the patient) and sagittal reformatted image processed with bone filters **(C)**. The white arrows indicate deformation of the frontal bone. The black arrow indicates the leftward shift of the nasal septum. Note the diffuse, homogeneous filling of the left and right sinus compartments with hypoattenuating fluid material; HU of the sinus content in this patient was 17.

of trephination, these compartments contained a clear non-purulent fluid. Bacteriological culture was performed in two cases, which resulted in negative outcomes. No bacteriological culture was performed of the contents from the horse that had prior trephination. Cytology was not performed in any of the cases. Exploration of the emptied sinuses did not reveal other pathological conditions in all animals. Profuse bleeding following perforation of the dorsal conchal sinus floor necessitated packing the sinus compartment with gauze bandages in case 1. In all other cases, minimal bleeding occurred and was controlled using temporary pressure with gauze sponges. Silicone tubes ($n = 5$) or Foley catheters ($n = 1$) were introduced into the affected nasal passages and fixed (**Figure 4**). In case 3 with bilateral sinus disease, a tracheotomy was performed to facilitate breathing before recovery from anesthesia. Mean surgery time was 64 min (±17).

Premature loss of tubes/Foley catheters was recorded in three cases after 3 (case 1), 5 (case 7), and 6 days (case 2), respectively. No attempts were made to replace these. In two other cases (4 and 5), tube fixation at the level of the nostrils was observed to loosen after 2 days and 2 weeks, respectively, which was subsequently restored by replacing the fixation sutures. A period of 3 weeks during which tubes could be kept in place was achieved in four of seven cases. Wound healing of sinusotomy incisions

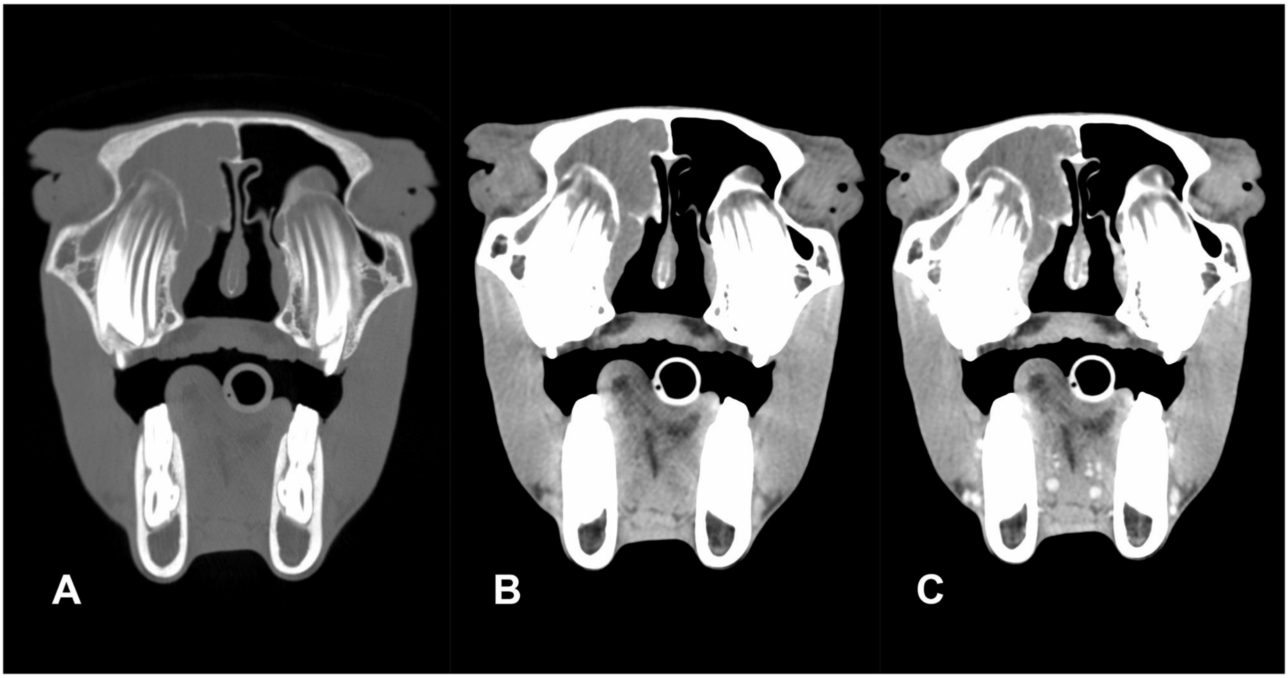


**FIGURE 3 |** Transverse pre-contrast CT images of an American miniature horse with unilateral disease (case 5) processed with bone **(A)** and soft tissue **(B)** filters and post-contrast CT image **(C)** (left in the image is right of the patient): the right sinus compartments were diffusely filled with fluid attenuating material (HU: 20). There is subtle leftward deviation of the nasal septum. There is mild contrast enhancement of the mucosal lining of the concho-frontal sinus but no enhancement of the sinus content.

was straightforward in all cases. A pre-operative existing local wound infection present at the right trephination site in case 2 required daily post-operative wound care consisting of regular (two to three times per day) disinfection (chlorhexidine 0.1%) and application of a chlorhexidine diacetate containing wound ointment. Swelling and drainage of pus resolved within 3 weeks. Post-operative endoscopy was performed in three of seven animals (cases 2, 4, and 6) at varying time intervals (3, 4, and 8 weeks post-op respectively). These examinations showed complete resolution of obstruction of the nasal passages and did not reveal any anomalies at the level of the natural apertures. The surgical fenestration was visualized and still patent in two of these animals (cases 2 and 6). Both had experienced premature loss of the draining tubes.

Radiographic follow-up was available for cases 2 and 5; in both patients, there was resolution of the soft tissue opacity of the affected sinus compartments. Both patients demonstrated mild to moderate bony changes such as periosteal reaction, thickening, and mild deformation of the frontal bone related to the surgery site.

Long-term outcome following a median period of 19 months was very good in all cases. Occasional mucus discharge was reported in two of seven cases (2 and 7). Cosmetic outcome was considered good in six of seven cases; only one case (1) reported a small permanent bump at the level of the surgical incision. Respiratory noise when running was reported in two of seven cases (3 and 7) without interfering with performance.

## DISCUSSION

Idiopathic sino-nasal obstruction is very rarely encountered in horses. This is reflected in veterinary literature by the publication of only two papers over six decades addressing this problem, which, based on our results, seems to be specifically associated with miniature horse breeds of younger ages (12, 13). Common causes for occlusion of sino-nasal communication such as chronic infection, trauma, or previous surgery were all excluded in these cases. Underlying allergic causes were not examined preoperatively but the absence of continued nasal discharge following surgical treatment in the majority of animals also makes this very unlikely. The bilateral presentation of the problem in six of seven animals at a very young age suggests a developmental origin and possible breed predisposition. Unfortunately, preoperative endoscopic evaluation of the nasomaxillary aperture was not possible in most cases as the endoscope could not be advanced sufficiently into the nasal passages. Post-operative endoscopy performed in three of seven animals at varying time intervals did not reveal anomalies at the level of the natural apertures. The presence of large reserve dental crowns disproportionate to the size of these animals' skulls (that is common in small breeds) might have also contributed to an obstructive effect on normal nasomaxillary clearance mechanisms. Complete obstruction of any sino-nasal communication was only encountered in one animal with no nasal discharge whose signs progressed to severe respiratory

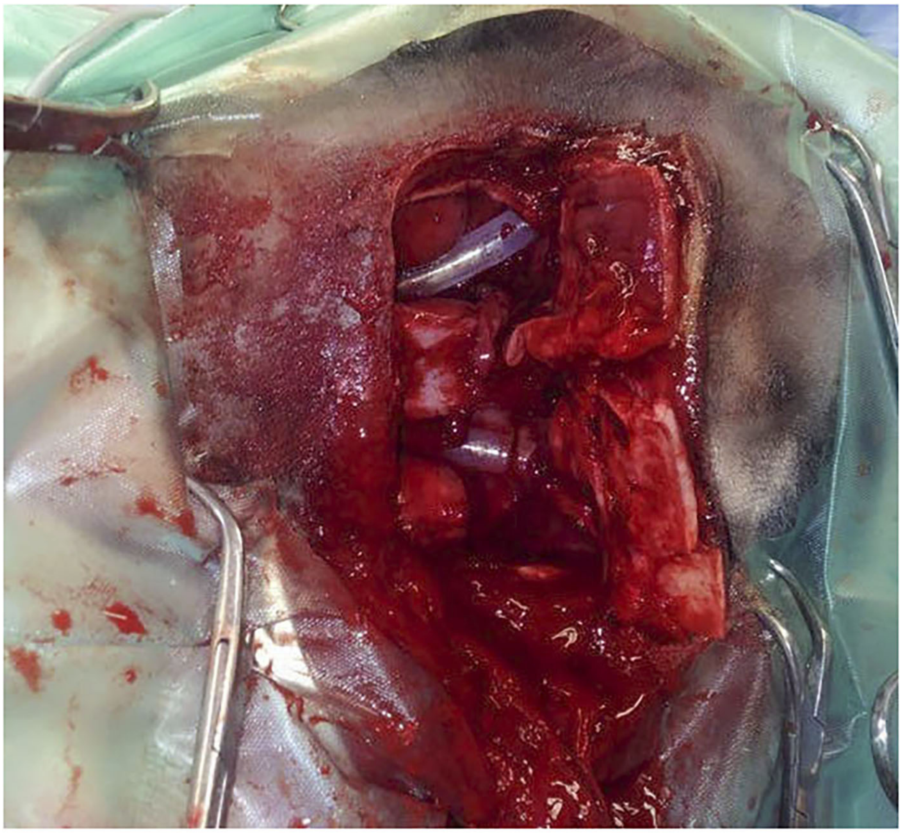

**FIGURE 4 |** Intra-operative dorsal view of a bilateral fronto-nasal bone flap osteotomy in a Miniature horse (case 3) with obstructive disease of the sino-nasal passages. Animal in left lateral recumbency. The bone flap is opened and silicone tubes have been introduced in both nasal passages after perforation of the medioventral wall of the dorsal concha.

airflow obstruction characterized by open mouth breathing. This illustrated the potentially progressive nature of the disease. Initial conservative treatments by administration of antibiotics and/or NSAIDs were unsuccessful in all animals.

A comparable syndrome to that described in the present paper, termed “sinus mucocele,” was previously reported in a 6-year-old American miniature horse (13). An older report (12) mentioned treatment of a unilateral accumulation of fluid in the sinus, which was called “mucocele sinusitis.” In humans, confusing descriptions of sinus mucocele have been reported including “cyst-like” as well as “thick-walled” structures (16). The lining is reported to be mucoperiosteum (17) or respiratory epithelium (18), and their location has been reported to be under the periosteum, which explains their potentially destructive effects due to expansile properties that cause erosion and remodeling of surrounding bony structures (17). None of these characteristics have been recorded in the present equine study where a mere accumulation of normal secretion from the sinus respiratory mucosa within the predefined sinus cavities was found. Although this accumulation caused important distortion of the inner sinus outlines, external bony deformations were only observed in one animal with focal outward bulging of the frontal bone and thinning of the bone due to pressure osteolysis. In equine paranasal sinus cysts, the presence of osteoclastic giant cells is thought to be responsible for the remodeling because of distension fluid pressure resulting in commonly reported facial swellings (18). Deformation of the skull as was observed in a second animal was related to infection of a former trephination site presenting with periosteal reactions and subcutaneous abscess formation. Because of these discrepancies, the authors preferred not to use the term “mucocele” for the encountered pathology.

The imaging features recorded in the present study have some similarities with the appearance of paranasal sinus cysts. Paranasal sinus cysts are commonly unilateral; bilateral disease is only rarely reported. In a recent study (19) investigating CT characteristics of paranasal sinus cysts, seven of eight cysts demonstrated a soft tissue to mineral attenuating wall; this finding was not detected in this case series of sino-nasal obstruction. Paranasal sinus cysts are typically expansile lesions; therefore, bone distortion is a common finding. In one patient in our case series, a true distortion of the frontal bone was present. This was on the side of the most severely affected sinus complex, and marked septal deviation toward the contralateral less affected side was also present. Duration of the disease in this patient was not significantly longer than in the other patients of this case series. Varying degrees of septal deviation away from the most severely affected sinus complex was a common finding, indicating that fluid accumulation associated with this pathology can increase pressure on the affected side. Primary sinusitis also presents as diffuse fluid accumulation in the affected sinus complex, which is purulent. Primary sinusitis is, however, rarely bilateral. Recorded HU of the sinus content varied from 1 to 25 in this case series. In one patient, the measured HU values were slightly higher; however, during surgery, the fluid content in this patient did not have different characteristics compared to the other patients. The CT study of this patient demonstrated some streaking artifacts, which could be responsible for this difference. In the patient with secondary infection following trephination, the recorded values did not differ from those measured in sinus compartments filled with clear fluid. A recent study demonstrated that HU measurements are not reliable to differentiate between cyst fluid and sinus mucus or exudate (19). Recorded HU were in the same range as those measured in the present study excluding HU as a means of differentiating between primary sinusitis and the idiopathic pathology in this case series.

The treatment performed included surgical sinus access through a large fronto-nasal bone flap osteotomy and perforating the conchal wall for re-establishment of more permanent drainage to the nose proved to be successful for all cases without recurrence of fluid accumulation. However, a more minimally invasive approach, such as transendoscopic laser fenestration (20, 21) or endoscopy-guided transnasal conchotomy (22, 23), might be more sufficient to restore sino-nasal drainage in these cases. However, the obstructed nasal passages precluded such an approach. The surgical fenestrations that were created in the present case series were large enough to stay patent in the long term as was confirmed endoscopically in two patients or remained at least patent until re-establishment of the natural aperture following age-related changes in the relationship between teeth and sinus structures. Patency of surgical fenestrations was not negatively influenced by premature tube loss, which questions the necessity of using these tubes for this purpose. The size of the fenestrations is most likely more important to maintain patency in the long term. Re-examining treated animals with endoscopy would enable to make more definite conclusions.

Surgical fenestration in the medioventral wall of the ventral conchal sinus (VCS) would have facilitated greater fluid loss than the more dorsal position used in this case series. However, the floor of the dorsal conchal sinus was preferred as the perforation site because of easiness of access to this region compared to the VCS. The presence of large reserve crowns in these young animals precluded access or only allowed blinded access to the VCS. The chances of causing important bleeding in a location that was difficult to access were considered much higher and thus not preferred. Use of a recently reported digital depression technique could have prevented hemorrhage such as was encountered in one case and might have resulted in adequate drainage in a more ventral position than that reported in the present case series (24).

Long-term outcome following a surgical fronto-nasal sinusotomy approach and nasomaxillary drainage repair for treatment of sino-nasal obstruction in miniature pony breeds achieved satisfactory outcomes with acceptable complications. Miniature equine breeds seem to be susceptible to the development of this rarely encountered sinus pathology and are particularly vulnerable at an age range where the developing dentition causes additional compression of the nasal passages. This should be considered in the differential diagnosis of progressive facial deformation and associated respiratory noises in these breeds.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the animal study because this is a retrospective study that didn't include any experimental aspects. Written informed consent for participation was not obtained from the owners because the study was a retrospective study where the research was initiated months after surgical correction of a disease problem was done. All owners were contacted by telephone inquire and questioned about participating to the study. They all agreed and provided the necessary information for the follow-up part of the study.

## AUTHOR CONTRIBUTIONS

LV was responsible for conceptualization, writing (original draft preparation), and editing. ER was responsible for writing (original draft preparation) and editing. All other authors contributed to reviewing and editing.

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# Fracture Resistance of Equine Cheek Teeth With and Without Occlusal Fissures: A Standardized *ex vivo* Model

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**Background:** *Ex vivo* fracture models are frequently used in human dentistry to provide insights in the fracture mechanisms of teeth. Equine cheek teeth fractures are an important dental pathology, but there has been no research performed to examine the fracture resistance *ex vivo*.

**Objective:** To evaluate the fracture resistance of equine cheek teeth and identify anatomical predictors that might influence fracture resistance in healthy teeth. It was further evaluated if the presence of a fissure caused a decrease in fracture resistance.

**Study design:** *Ex vivo* experimental design.

**Methods:** Individual cheek teeth were subjected to a compression load in a universal testing machine until fracture occurred. Testing was performed in two study groups. A first group of healthy cheek teeth was tested to examine anatomical predictors on fracture resistance. A second group comprised cheek teeth with occlusal fissures and an equal number of age- and size-matched fissure-free teeth as controls. The effect of possible predictors on fracture resistance was investigated by regression analysis.

**Results:** In the first group, fracture resistance was significantly influenced by the location on the tooth where testing was performed in both maxillary ($p < 0.001$) and mandibular teeth ($p < 0.001$). Additional significantly associated factors were Triadan number in mandibular ($p = 0.009$) and the mesiodistal length of the occlusal surface of maxillary teeth ($p = 0.01$). Experimentally induced crown fractures that extended below the simulated bone level were more frequently associated with pulp horn exposure ($p < 0.001$). In the second group, significant lower fracture loads were recorded in teeth with fissures (mandibular $p = 0.006$; maxillary $p < 0.001$), compared to fissure-free teeth.

**Main limitations:** This *ex vivo* model does not imitate the *in vivo* masticatory forces and lacks the shock-absorbing properties of the periodontal ligament.

**Conclusions:** The methodology used in this study provides an *ex vivo* experimental set-up to test fracture resistance of equine cheek teeth enabling evidence-based research to examine the potentially weakening effects of tooth pathology and its treatments. Crown resistance to fracture differed along the occlusal surface of healthy equine cheek teeth, and the presence of fissures further decreased fracture resistance.

**Keywords: equine, cheek tooth, fracture, fracture resistance, fissure**

## INTRODUCTION

The cheek teeth of horses play a very important role in the horse's digestive strategy since it is characterized by a high chewing efficiency (1). During the mastication process considerable forces are developed which have an effect on the tooth (and its surrounding structures) (2, 3). However, it is not known to which extent an equine tooth can cope with these forces and when the critical point to fracture is reached.

Equine cheek teeth fractures are considered an important dental pathological disorder which can have serious consequences for the well-being of the horse. Different fracture patterns have been described, but only the etiology of maxillary sagittal midline fractures has been discovered. This fracture type is considered to develop secondary to advanced infundibular caries and therefore is referred to as caries related infundibular fractures (4–6). However, other fracture patterns remain idiopathic (4–9). It has been suggested that these idiopathic fractures occur on sites of structural weakness (5), but the fracture resistance of equine cheek teeth and the possible difference in fracture tolerance at specific locations on the tooth has not been examined up to date. Furthermore, information is lacking whether there are characteristics of the tooth (e.g., age-dependent changes) that influence the ability to withstand masticatory forces. In human teeth it has been demonstrated that young teeth have a higher fracture susceptibility because of their wide root canals and relative lower presence of mineralized tissues (dentin) (10, 11). In contrast, the median age of horses with a fractured tooth is reported to be 11–12 years (6, 8), which indicates a decrease in strength with age. Recently, attention has been brought to the presence of fissures on the occlusal surface of equine cheek teeth and their ability to progress into gross crown fractures (12). Therefore, we hypothesize that the presence of occlusal fissures causes a lower fracture resistance compared to cheek teeth without fissures.

The aim of this study was to determine the fracture resistance of equine cheek teeth in an *ex vivo* experiment. Hereby, it was intended to examine the possible differences in fracture resistance between specific locations on the tooth, the effect of age and the effect of the dimensions of the occlusal surface. Additionally, the impact of the presence of a fissure on fracture resistance was examined.

**Abbreviations:** SD-PH, secondary dentine above pulp horn.

## MATERIALS AND METHODS

### Study Design and Study Populations

An *ex vivo* experimental study was conducted on individual cheek teeth to examine their fracture resistance. Equine cheek teeth (Triadan 07–10) were extracted post-mortem (within 24 h after dead) from horses either euthanized for non-dental related problems or obtained from an abattoir in Belgium in 2020. Clinical information was available for the euthanized horses and the age of cadavers from the abattoir was estimated by mandibular incisor examination by one person (EP) (13). Only teeth without any signs of clinical dental pathology (except fissures) were included in the study. Surrounding tissues (bone, periodontal ligament) were removed from the teeth and the occlusal surface was inspected for the absence or presence of fissures. When a fissure was present, the fissure type (**Table 1**) (14) and the location of the fissure on the occlusal surface were recorded. Macro photographic images (5MP, Samsung galaxy A51) were taken of the occlusal surface of all teeth to ensure that no fissures were missed. The width (buccal-lingual distance) and length (mesio-distal distance) of each tooth's occlusal surface was measured with a caliper. Teeth were stored in 0.5% chloramine T trihydrate at 4°C until further processing.

High-resolution X-ray computed tomography (μCT) imaging was performed on teeth with fissures at the in-house developed μCT system HECTOR (15) of the Ghent University Centre for X-ray Tomography (UGCT). Covering a rotation of 360°, 2,000 projection images were made at an exposure time of 1,000 ms each. Using geometrical magnification, an isotropic voxel size of $50.136^3$ $\mu m^3$ is achieved in the reconstructed volume, reconstructed using Octopus Reconstruction. At the source parameters of 150 kV and 30 W target power, the influence of spot blurring is negligible. Beam hardening was countered both in hardware by adding 1 mm Al filter and in the reconstruction software. The depth of each fissure was measured as illustrated in **Supplementary Image 1**.

Testing was performed in two study groups. The number of teeth used was based on the availability of cadaver heads. The first study population consisted of healthy cheek teeth without abnormalities to examine individual and anatomical predictors that could influence the fracture resistance of the tooth. In

**TABLE 1 |** Fissure classification (14).

| Fissure type | Definition |
|---|---|
| Type 1 | Fissures that involve the secondary dentin on the occlusal surface |
| 1a | Fissure orientation is perpendicular to the surrounding enamel fold, variably involving the adjacent enamel or even the peripheral cementum |
| 1b | Fissure orientation does not follow a perpendicular orientation in relation to one surrounding enamel fold. Often this orientation is more mesio-distal. |
| Type 2 | Fissures that do not involve the secondary dentin |

this group only teeth of horses with a known age were used. A schematic representation of the different occlusal locations where mechanical pressure was exerted is illustrated in **Figure 1**. One or two locations were tested on the same tooth (a second location was tested only if the first loaded site did not result in a fracture involving a significant part of the tooth and after re-inspection of the tooth for induced cracks in the remaining part of the tooth). The second study population comprised cheek teeth with macroscopically identified occlusal fissures, and an equal number of age- and size-matched fissure-free teeth selected as controls. Mechanical testing of sites where a fissure type 1a was present, was performed by placing the tip of the device on the location where the fissure entered the secondary dentin. The same approach was performed for type 1b fissures. When a type 1b fissure involved the secondary dentine above two different pulp horns, the tip was placed on the secondary dentin at the side where the fissure ran closest to/ breached through the outer enamel ring. For type 2 fissures, the tip was positioned on the most axial site of the fissure on the occlusal surface. The tip was positioned on the same site for matched teeth.

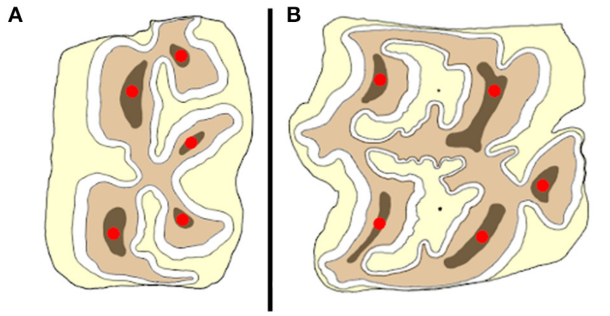


**FIGURE 1 |** Schematic illustration of the placement of the tip of the compression device (red dots) on a mandibular **(A)** and maxillary **(B)** cheek tooth at different anatomical locations.

## *Ex vivo* Fracture Resistance Set-Up

The teeth were embedded in resin blocks (Palapress®, Kulzer Benelux, Haarlem, The Netherlands) within polyvinyl chloride (PVC) cylinders (5 cm outer diameter, 8–9 cm high). The level of the resin was fixed at 15 mm below the occlusal surface for every tooth, measured from the mid-point of the tooth at the interproximal surfaces, to approximate the normal bone level on the tooth (**Figure 2**). Immediately upon setting of the resin, the specimen was placed in cool water to dissipate the heat of polymerization of the resin. To prevent dehydration of the mounted tooth until final processing, the specimens were kept in demineralized water.

Between 2 and 8 h after the embedding process, specimens were subjected to a load at a crosshead speed of 1 $mm.min^{-1}$ in a universal testing machine (LRX plus, loadcell 5000N, LLOYD instruments, Ametek Inc.) until a fracture occurred. For the purpose of this study, point pressure was chosen to be able to test different areas on the occlusal surface. Pressure was exerted with a custom-made compression device (triangular shape, tip diameter 2 mm) which was positioned on the predefined site on the occlusal surface (**Figure 3**). The failure (fracture) load (N) of each site was recorded. The highest force prior to fracture was considered the maximum force sustained by the tooth. Inspection of the tooth after fracturing included recording of the fracture pattern, fracture level (above, equal to or below the simulated bone level), and whether the pulp cavity was exposed or not.

## Data Analysis

Categorical variables were expressed as numbers and percentages. Continuous variables were presented as mean ± standard deviation (and range, when interesting). Two major outcomes were assessed (fracture resistance and fracture level) in two different groups of teeth.

In the first study group (teeth with no abnormalities), the fracture resistance and the fracture level (above/equal/below the simulated bone level) of mandibular and maxillary cheek teeth were compared using mixed models with mandible/maxilla as fixed effect and horse as random effect. The effect of the fracture level (independent variable) on the occurrence of pulp exposure (dependent variable) was compared with a mixed model with horse as random effect. The age of the teeth (dependent variable) with and without pulp exposure (independent variable) was also compared with a mixed model with horse as random effect.

For the subsequent analyses, mandibular and maxillary cheek teeth were analyzed separately due to the anatomical difference between the respective teeth. An ANOVA was conducted to compare the fracture resistance between horses to assess whether there was variability by horse. Subsequently, effect of individual predictors, i.e., gender (male/female), jaw side (left/right), tooth number (Triadan 07 – 10), age of the tooth, tooth side (lingual/buccal), location on the tooth [secondary dentine above pulp horn (SD-PH) 1 – 5] and occlusal surface width, length and surface area (width × length) on fracture resistance was assessed with a linear mixed model with the individual predictor as fixed effect and horse as random effect. Furthermore, the effect of location on the tooth on fracture level was also assessed. Significance was assessed with a likelihood ratio test.

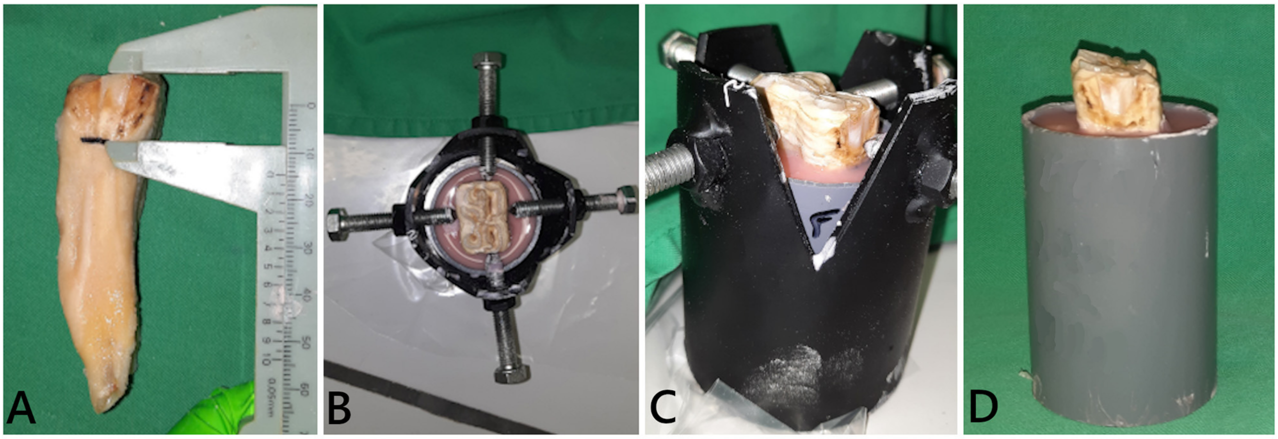


**FIGURE 2 |** Embedding of a tooth in resin blocks. **(A)** The simulated bone level was determined on a tooth stripped of periodontal ligament. The tooth was fixed in a custom-made holder at the desired height and position [**(B)** dorsal view; **(C)** side view]. **(D)** Final tooth fixation.

*P*-values were corrected for multiple testing by multiplying them by the number of tests and are reported as such. Next, the most optimal generalized mixed model was determined based on the combination of predictors that minimized the Akaike Information.

In the second study group, the overall average fracture resistance of cheek teeth with and without fissures was compared with a linear mixed model with the presence of fissure (yes/no) as fixed effect and horse as random effect. The fracture level of teeth with and without fissures was also compared with a mixed model with horse as random effect. A similar approach as described for the first study group with separate analysis for mandibular and maxillary cheek teeth was used for the remainder of the analyses, i.e., a mixed model with the addition of presence of fissure (yes/no) and fissure type (0, 1a, 1b, 2) as individual predictors.

For all mixed model analyses with a categorial variable with more than 2 categories as the dependent variable, the Begg and Gray Approximation was used. The overall significance was set at $\alpha \leq 0.05$. The program R version 4.0.2 ("Taking off again") was used for all analyses (16).

## RESULTS

### *Ex vivo* Fracture Resistance of Equine Cheek Teeth With No Abnormalities

Fifty-nine healthy cheek teeth from seven horses (four mares, three geldings) were included to examine possible factors that influenced fracture resistance of equine cheek teeth. These included 28 mandibular cheek teeth with a mean dental age of 9.0 ± 2.0 years (min 5 y, max 12 y), 8 of which were Triadan 07s, 7 Triadan 08s, 7 Triadan 09s and 6 Triadan 10s. Their average occlusal surface width was 19.9 ± 1.5 mm (min 17 mm, max 23 mm) and the average occlusal surface length was 28.4 ± 1.5 mm (min 26 mm, max 31 mm). Furthermore, 31 maxillary cheek teeth with a mean dental age of 9.2 ± 2.0 years old (min 5 y, max 12 y) were included, consisting of 7 Triadan 07s, 10 Triadan 08s, 5 Triadan 09s and 9 Triadan 10s. These teeth had an average occlusal surface width of 28.9 ± 1.3 mm (min 27 mm, max 31 mm) and an average occlusal surface length of 28.1 ± 1.6 mm (min 25 mm, max 31 mm). An overview of the locations tested per tooth can be found in **Supplementary Information 1**.

The mean maximum force sustained by the tested teeth was 2,373.34 ± 583.94 N (min: 1,422.7 N; max: 3,769.7 N). There was no significant difference in mean maximum force between mandibular (2,336.58 ± 485.59 N) and maxillary (2,410.73 ± 673.57 N) cheek teeth ($p = 0.64$). For both the mandible ($p \leq 0.01$) and the maxilla ($p \leq 0.001$), there was a significant variability between horses. In the mandible, the side of the tooth (buccal/ lingual) ($p = 0.01$) and location on the tooth (SD-PH 1-5) ($p < 0.001$) were significant factors in the univariate model (**Supplementary Information 2**). In the final multiple regression model of the mandible, the location on the tooth (SD-PH 1-5) ($p < 0.001$) and the Triadan number ($p = 0.009$) remained significant (**Table 2**). The highest fracture resistance was found on the level of the SD-PH 2, followed by SD-PH 4, 1, 3, and 5 (**Figure 4**). In the maxilla, the sustained maximum force was significantly different between locations on the tooth in the univariate model ($p < 0.001$) (**Supplementary Information 2**), which remained significant in the final multiple regression model ($p < 0.001$) (**Table 2**). In maxillary cheek teeth, the tooth had the highest fracture resistance at the level of the SD-PH 4, followed by SD-PH 1, 3, 2, and 5 (**Figure 4**). Additionally, a significant effect of the mesio-distal length of the occlucal surface ($p = 0.01$) on fracture resistance was withheld in the final multiple regression model.

Observed fracture patterns are illustrated in **Supplementary Information 3**. The tooth broke above ($n = 33/89$; 37.1%), equal to ($n = 29/89$; 32.6%) or below ($n = 27/89$; 30.3%) the simulated bone level at similar frequencies. Significantly more fractures below the simulated bone level were recorded in maxillary ($n = 19/44$) compared to mandibular teeth ($n = 8/45$) ($p = 0.001$). No difference was observed

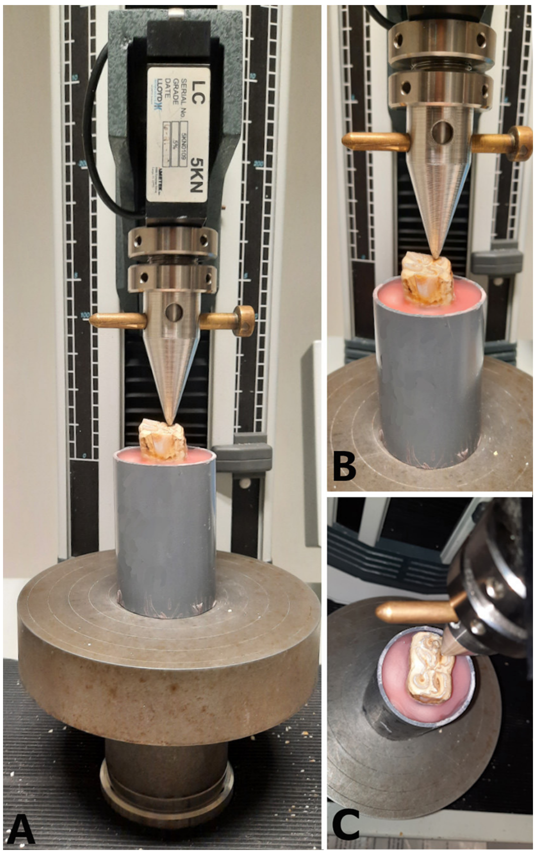


**FIGURE 3 |** Representation of the application of a compressive force to the occlusal surface of a mandibular cheek tooth at the level of the secondary dentine above pulp horn 2. **(A)** Frontal view of the specimen placed under the compression device attached to a 5,000 N load cell. **(B)** Close up of the front view centered on the tooth. **(C)** Dorsal view of the positioning of the compression device.

between fracture levels in relation to different tested occlusal sites (SD-PH) on mandibular teeth. In maxillary teeth there was a significant difference in the number of fractures above and below the simulated bone level in relation to occlusal test sites ($p = 0.02$)(**Supplementary Information 4**).

In 25/89 (28.1 %) cases the pulp cavity became exposed. In most cases, the pulp horn associated with the testing site was involved (20/25). Additionally, in 3 out of 20 cases, a second pulp horn was exposed. In 5/25 cases, a pulp horn became exposed which was not situated directly beneath the site where the pressure was exerted. It was observed that the location of pulp horn exposure was usually not at the most apical aspect of the fracture, but along the fracture plane (**Figure 5**). The mean age of teeth with an exposed pulp cavity was 8.64 ± 2.34 years old which was similar to the mean age of teeth without exposed pulp cavities (9.05 ± 1.84 years old, $p = 0.5$). Pulp cavities were exposed significantly more when the fracture level was below ($p < 0.001$) or equal to ($p = 0.03$) the simulated bone level. In only 1 out of 33 cases, a pulp horn was exposed after fracturing above the simulated bone level (Triadan 110, pulp horn 5, dental age 7 years). In 6 (out of 29) and 18 (out of 27) cases, the pulp cavity was exposed when the fracture was equal to and below the simulated bone level, respectively. The distribution of cases with exposed pulp cavities in relation to the fracture level is illustrated in **Figure 6**.

## Does the Presence of a Fissure Influence Fracture Resistance of Equine Cheek Teeth?

Teeth from 17 different horses were included in this part of the study. Forty-two cheek teeth (21 maxillary, 21 mandibular) with fissures were randomly selected. Mandibular cheek teeth had a mean dental age of 10.2 ± 1.6 years old (min 7 y, max 12 y) including 3 Triadan 07s, 4 Triadan 08s, 9 Triadan 09s and 5 Triadan 10s. Fissure classification involved type 1a in 12, type 1b in 8 and type 2 in 1 tooth, respectively. These teeth had an average occlusal surface width of 19.1 ± 1.9 mm (min 16 mm, max 22 mm) and an average occlusal surface length of 27.0 ± 1.7 mm (min 24 mm, max 30 mm). Maxillary cheek teeth had a mean dental age of 10.3 ± 1.4 years old (min 8 y, max 12 y) including 3 Triadan 07s, 4 Triadan 08s, 8 Triadan 09s and 6 Triadan 10s. Fissure classification involved type 1a in 14, type 1b in 5 and type 2 in 2 teeth, respectively. Their average occlusal surface width was 28.1 ± 1.9 mm (min 25 mm, max 31 mm) and their average occlusal surface length was 26.4 ± 1.9 mm (min 23 mm, max 31 mm). The average fissure depth of fissures in this population was 9.99 ± 5.43 mm (min 0.35; max 21.00 mm) and 8.83 ± 4.90 mm (min 2.73; max 20.60 mm) in mandibular and maxillary cheek teeth, respectively. A detailed overview of the distribution of teeth with fissures can be found in **Supplementary Information 5**. An age- and size matched tooth without fissures was selected as control (mean age of 10.00 ± 1.41 years and 10.14 ± 1.24 years; mean width of 19.0 ± 1.8 mm and 28.1 ± 1.5 mm; mean length of 27.1 ± 1.7 mm and 26.5 ± 1.8 mm of mandibular and maxillary control teeth, respectively).

The mean maximum force sustained by teeth with fissures was 1,974.02 ± 402.09 N (min 1,142.9, max 3,087.0) compared to 2,594.70 ± 548.51 N (min 1,389.9, max 3,769.7 N) in teeth without fissures. The sustained maximum force was on average 529.27 N lower in cheek teeth with fissures (95% CI: 318.39; 740.16, $p < 0.001$). In the mandible, only fissure type was a significant predictor in the univariate analysis ($p = 0.006$). In the maxilla, the general presence of a fissure ($p < 0.001$) and fissure type ($p < 0.001$) were significant (**Supplementary Information 6**). In the final multiple regression model, fissure type remained significant in both the mandible ($p = 0.006$) and the maxilla ($p < 0.001$) (**Table 3**). The mean sustained maximum force in cheek teeth with and without fissures in the mandible and maxilla can be found in **Figure 7**. Furthermore, in mandibular teeth, location on the tooth (SD-PH 1-5) ($p = 0.005$), the age of the tooth ($p = 0.006$), the length of the tooth ($p < 0.001$) and the side of the jaw (left/ right) ($p = 0.05$) were significantly associated with a lower/higher fracture resistance. In maxillary teeth, only the location on the tooth (SD-PH 1-5) ($p < 0.001$) demonstrated a significant association,

**TABLE 2 |** Results of the final multivariable model of factors significantly influencing the fracture resistance of cheek teeth in the first study population.

| | Category | Estimate | SE | 95% CI | *p*-value |
|---|---|---|---|---|---|
| **Mandible** | | | | | |
| Intercept | | 2,428.06 | 148.80 | 2,136.43; 2,719.69 | |
| SD-PH | 1 | Reference category | | | |
| | 2 | 107.46 | 114.98 | −117.89; 332.82 | 0.36 |
| | 3 | −194.14 | 118.78 | −426.94; 38.66 | 0.11 |
| | 4 | 53.70 | 155.80 | −251.66; 359.05 | 0.73 |
| | 5 | −756.40 | −756.40 | −995.28;−517.52 | <0.001 |
| Triadan | 07 | Reference category | | | |
| | 08 | 110.68 | 106.14 | −97.36; 318.72 | 0.30 |
| | 09 | −196.34 | 124.64 | −440.64; 47.96 | 0.12 |
| | 10 | 227.67 | 121.20 | −9.87; 465.21 | 0.07 |
| **Maxilla** | | | | | |
| Intercept | | 250.70 | 932.92 | −1,577.78; 2,079.19 | |
| SD-PH | 1 | Reference category | | | |
| | 2 | −687.95 | 159.85 | −1,001.24; −374.65 | <0.001 |
| | 3 | −385.80 | 173.64 | −726.13; −45.47 | 0.01 |
| | 4 | 501.97 | 138.73 | 230.07; 773.88 | <0.001 |
| | 5 | −737.35 | 143.87 | −1,019.34; −455.37 | 0.01 |
| Length | Cont. | 82.68 | 32.93 | 18.13; 147.23 | 0.02 |

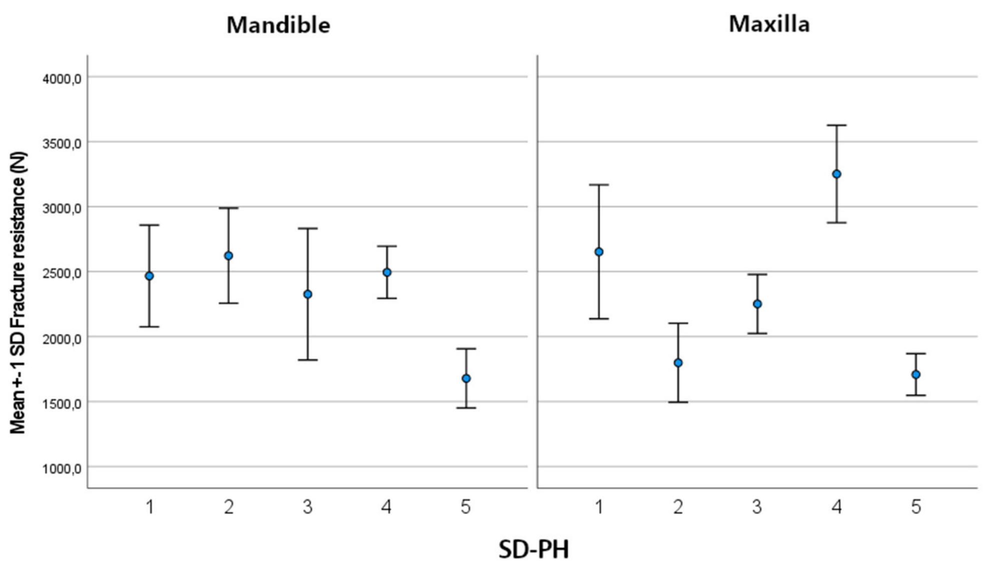


**FIGURE 4 |** Bar chart illustrating the mean and SD of the fracture resistance in mandibular and maxillary cheek teeth at different locations on the tooth.

besides the earlier mentioned fracture type. Detailed results of the examined predictors can be found in **Table 3**.

The way the tooth fractured (fracture pattern) was grossly similar between teeth with and without a fissure in 14/21 paired maxillary cheek teeth and in 13/21 paired mandibular teeth. It was observed that the fracture plane of teeth with fissures was always discolored compared to teeth without fissures (**Figure 8**). There was no significant difference between fracture levels in cheek teeth with and without fissures ($p = 0.25$, $p = 0.86$ and $p = 0.18$ for the comparison of fracture levels above vs. below, below vs. equal and above vs. equal the simulated bone level, respectively). In 7 teeth, the pulp cavity became exposed (1 tooth with a fissure and 6 without).

## DISCUSSION

This study examined the *ex vivo* fracture resistance of equine cheek teeth where individual (gender, age) and anatomical factors

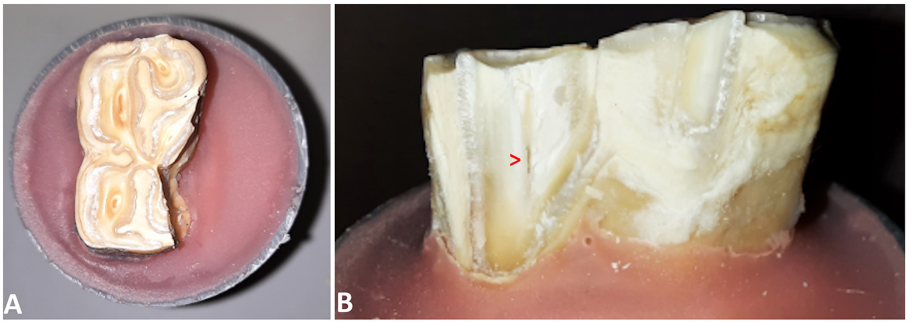


**FIGURE 5 | (A)** Occlusal view of a 407 after fracture testing at the level of the secondary dentine associated with pulp horn 3. **(B)** Lingual view of the tooth demonstrating the exposed pulp cavity.

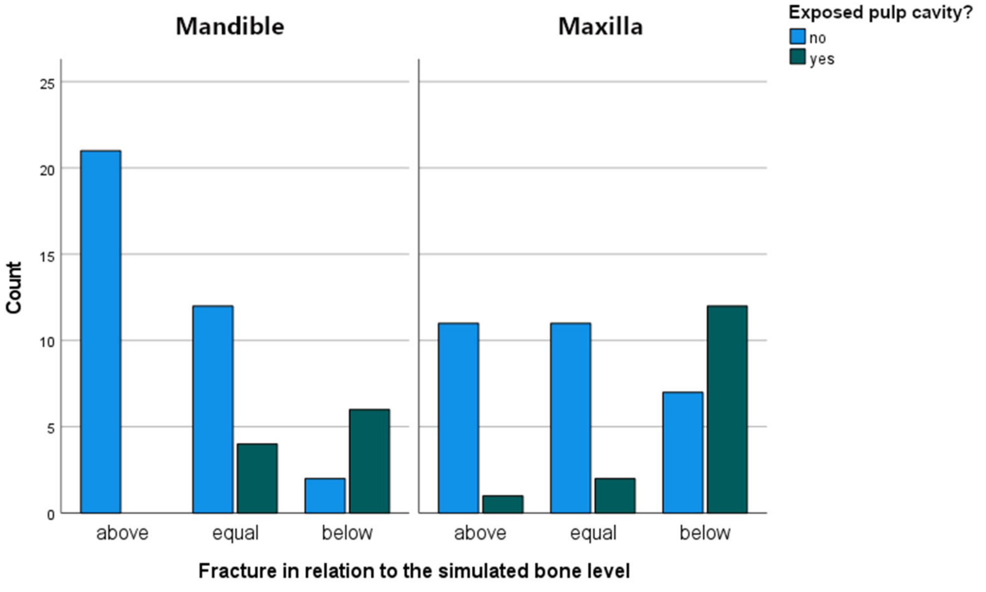


**FIGURE 6 |** Bar chart illustrating the number of cases with exposed pulp cavities in relationship to the fracture level in the mandibular and maxillary cheek.

(Triadan number, the site of impact (SD-PH 1-5), dimensions of the occlusal surface) of the tooth were taken into consideration. A significant influence of the anatomical site where the impact on the tooth occurs in both maxillary and mandibular teeth was demonstrated, as was the Triadan number in mandibular teeth and the mesio-distal length of the occlusal surface in maxillary cheek teeth. Additionally, it was demonstrated that fissures on the occlusal surface decreased the fracture resistance in both mandibular and maxillary cheek teeth.

To the author's knowledge, this is the first study examining the *ex vivo* fracture resistance of equine teeth. The methodology used in this study is similar to most human-fracture resistance studies where the tooth is submitted to a continuously increasing force until it fractures. This type of impact is force regulated and carried out with a servo-hydraulic test machine (17). As this is an *ex vivo* study, there are of course limitations. The impact speed in the present study was set at 1 mm/min which is much lower than generated during the normal masticatory cycle. The test machine only allowed exerting forces in one direction which is in contrast to *in vivo* masticatory forces that act in 2 phases (vertical and oblique) during the chewing cycle (2, 3). Also, the set-up lacks the shock-absorbing properties of the periodontium (18, 19). Nevertheless, the fracture patterns generated in this experiment are highly similar to those described in previous studies (5, 12). This illustrates the clinical relevance of the model and also shows that it might be used for comparable experiments focusing on potentially weakening effects of other pathological factors (e.g., peripheral caries, infundibular caries, exposed pulp cavities) and provide an evidence-based approach for their treatment (e.g., infundibular restoration, root canal therapy). Another interesting future application involves research about dental floating. In equids, dental floating has become an established "routine" custom because of the perceived importance of the intervention by veterinarians and owners. Consequently, a critical evaluation

**TABLE 3 |** Final multivariable model of significant predictors on fracture resistance of the second study population.

| Variable | Category | Estimate | SE | 95% CI | *p*-value |
|---|---|---|---|---|---|
| **Mandible** | | | | | |
| Intercept | | −2,697.49 | 1,004.63 | −4,666.52, −728.46 | |
| Fissure | No | Reference category | | | |
| | Type 1a | –500.67 | 100.25 | –697.16; –304.18 | <0.001 |
| | Type 1b | –625.74 | 116.65 | –854.38; –397.11 | <0.001 |
| | Type 2 | −121.07 | 277.34 | –664.64; 422.51 | 0.67 |
| SD-PH | 1 | Reference category | | | |
| | 2 | 248.26 | 117.79 | 17.41; 479.12 | 0.04 |
| | 3 | 44.62 | 210.56 | –368.06; 457.30 | 0.21 |
| | 5 | –666.67 | 206.75 | –1,071.90; –261.44 | 0.003 |
| Age | Cont. | 171.95 | 34.18 | 104.96; 238.94 | <0.001 |
| Length | Cont. | 125.01 | 30.69 | 64.86; 185.16 | <0.001 |
| Jaw | Left | Reference category | | | |
| | Right | −161.06 | 90.32 | –338.08; 15.96 | 0.08 |
| **Maxilla** | | | | | |
| Intercept | | 2,231.03 | 211.29 | 1,816.91; 2,645.15 | |
| Fissure | No | Reference category | | | |
| | Type 1a | –758.28 | 128.43 | –1,010.00; –506.55 | <0.001 |
| | Type 1b | –536.78 | 209.19 | –946.78; –126.79 | 0.01 |
| | Type 2 | –1,307.72 | 366.22 | 2,025.49; –589.95 | <0.001 |
| SD-PH | 1 | Reference category | | | |
| | 3 | 185.10 | 240.86 | –286.98; 657.17 | 0.45 |
| | 4 | 819.67 | 227.71 | 373.36; 1,265.98 | 0.001 |
| | 5 | 136.05 | 260.16 | –373.85; 645.95 | 0.60 |

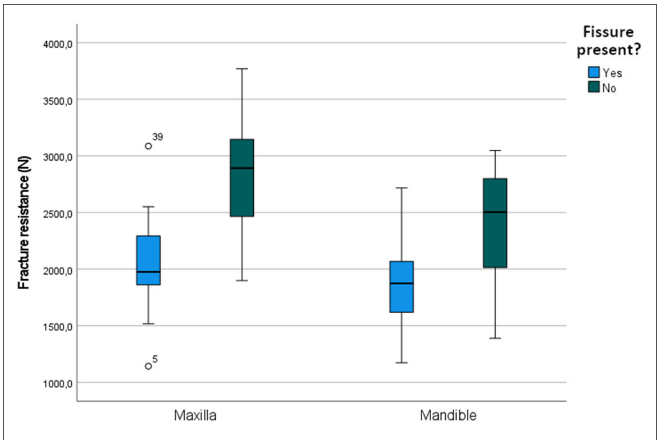


**FIGURE 7 |** Boxplot illustrating the fracture resistance of cheek teeth with and without fissures present in the maxilla and mandible.

of what is being achieved by so-called "occlusal equilibration" is often not performed (20) and evidence-based information on how that impacts the tooth's strength is not available. In human teeth, studies have emphasized the importance of maintaining dental structure to preserve the strength of the tooth (21, 22). One equine maxillary cheek tooth with excessive floating marks on the buccal side showed a fracture resistance of 1,093 N (at the level of the SD-PH 2) (unpublished data), which was lower than the tested cheek teeth in this study (min: 1,480 N on the same location). It therefore might be possible that the excessive floating had a negative impact on the fracture resistance of this tooth, which merits further investigation.

## *Ex vivo* Fracture Resistance of Equine Cheek Teeth With No Abnormalities

It has been suggested that the distribution of the mineralized tissues of an equine cheek tooth are a physiological requirement to cope with masticatory forces (23–25). An important finding in this study was the wide range in fracture resistance, with marked differences, depending on the region of the occlusal surface that was loaded. This indicates that there are anatomical areas with higher or lower intrinsic structural strength on the occlusal surface of equine cheek teeth. Kilic et al. reported that the enamel thickness was larger at the buccal aspect of the maxillary and the lingual aspect of the mandibular cheek teeth (23). However, Windley et al. recorded the largest thickness of enamel on the buccal side of mandibular teeth (26). Clinical papers reporting prevalence of cheek tooth fractures reflect these contradictory structural results. Uncomplicated crown fractures of both mandibular and maxillary cheek teeth were more frequently observed on the lingual side in one study (12), whereas idiopathic buccal slab fractures were more frequently reported in others (6, 8). These inconsistent findings illustrate

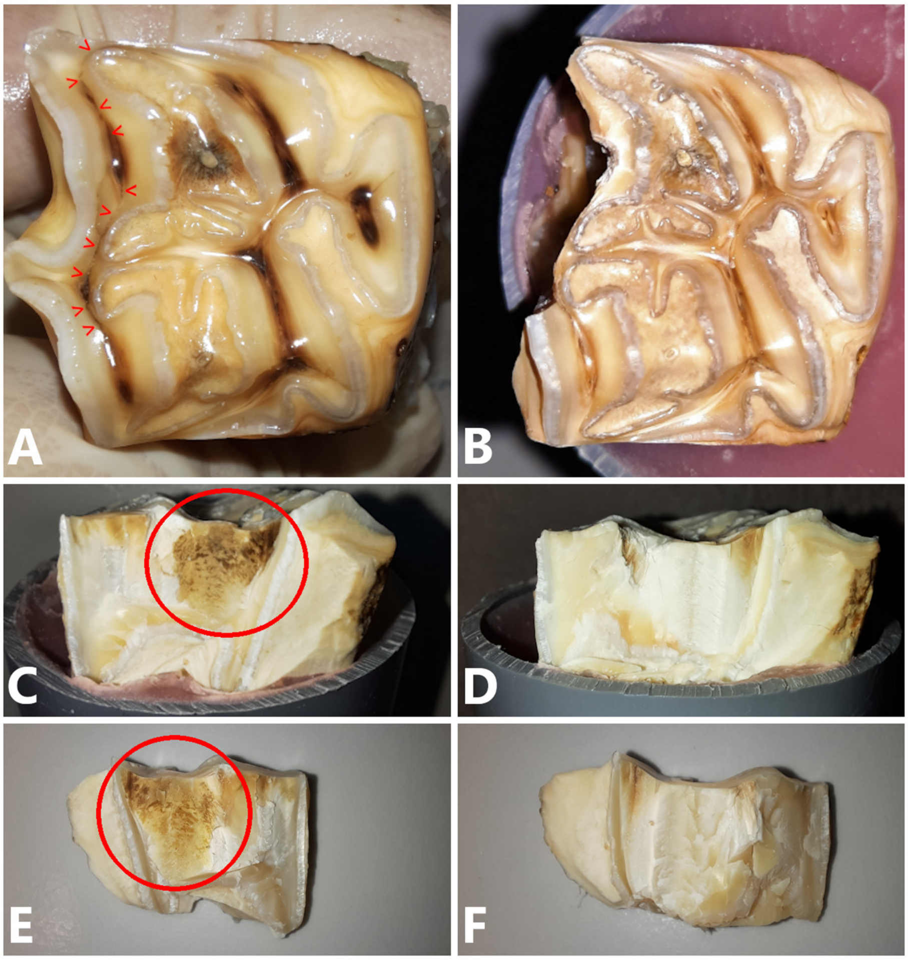


**FIGURE 8 | (A)** Occlusal view of a 109 cheek tooth with a type 1b fissure present (red arrow heads). Pressure was exerted at the level of SD-PH 1. **(B)** Occlusal view of the tooth after fracture testing. The fracture followed the path of the fissure approximating SD-PH 2. **(C)** Lateral view of the tooth after fracture testing. A brown discolored area is visible (red circle) as well as on the fracture fragment **(E)**. **(D,F)** No discoloration was visible on the tooth and fragment of the matched control tooth.

the complex multifactorial mechanism behind development of a tooth fracture. Our results indicate that a mandibular cheek tooth was the strongest on the buccal side of the tooth at the level of the SD-PH 2 (mean sustained maximum force of 2,622.682 N), followed by SD-PH 4 (2,494.74 N), SD-PH 1 (2,466.76 N), SD-PH 3 (2,326.15 N) and SD-PH 5 (1,678.35 N). In maxillary cheek teeth, the tooth was the strongest at the level of the SD-PH 4 (mean sustained maximum force of 3,251.06N), followed by SD-PH 1 (2,652.48 N), SD-PH 3 (2,251.52 N), SD-PH 2 (1,798.83 N) and SD-PH 5 (1,708.42 N). When comparing with the prevalence of uncomplicated fracture locations these results can explain why these fractures were more observed on the lingual side (12).The lower recorded fracture resistance at SD-PH2 level in maxillary cheek teeth also coincides with the higher prevalence of partial buccal slab fractures at this location compared to SD-PH1 (12). Kilic et al. furthermore reported that the overall enamel thickness in maxillary cheek teeth is thicker compared to mandibular cheek teeth which could suggest that maxillary cheek teeth are more capable of coping with masticatory forces (23). However, this was not supported in this study since the average fracture resistance of mandibular and maxillary cheek teeth was comparable (2,336.58 and 2,410.73 N, respectively). This might suggest that, in equine cheek teeth, the enamel thickness is not the primary factor determining fracture resistance.

The forces generated during equine mastication are reported to reach 1,956 N in young horses (3). The average *ex-vivo* fracture resistance in this study was higher (2,373.34 N), indicating that healthy teeth are overall well-equipped to cope with normal masticatory forces. Masticatory forces have been reported to increase from rostral to caudal (3), therefore it could be conjectured that teeth situated more caudally in the mouth should have a higher resistance to fracture. In the mandible, the Triadan number was a significant factor influencing the fracture resistance, with Triadan 10 (second molar) indeed displaying the highest ability to withstand fracture. However, Triadan 09 (first molar) had the lowest fracture resistance which does not follow this hypothesis. This tooth number has been reported as the one most frequently fractured (27), but this was not consistent with other studies (6, 8, 9). In the maxilla, the mesiodistal length of the occlusal surface was also a significant factor, with an increasing fracture resistance with increasing length. This demonstrates that larger teeth can be expected to sustain higher masticatory forces without fracture. It is somewhat surprising that factors that significantly influence the fracture resistance differ between the mandible and the maxilla, especially since both the triadan number and the mesiodistal length represent the amount of tooth that is present in and around the region of the testing device (28). This might be explained due to the different anatomy and distribution of dental tissues between the more narrow mandibular and wider maxillary cheek teeth. Ultrastructural differences between mandibular and maxillary teeth (e.g., the presence of a different ratio of enamel types) might further explain these differences (23). It has been demonstrated that the mesiodistal occlusal distance varies by triadan number (28), however these differences are relatively small and other ultrastructural characteristics between triadan numbers might be of more importance in regard to the tooth's capacity to withstand loading forces. Ultrastructural studies comparing the toughness of dental tissues in between tooth positions are unfortunately lacking to provide further insights.

Tooth age appeared to have no influence on the fracture resistance of cheek teeth in this study population. However, it has to be noted that the age-range of this study population (5–12 years) might not be wide enough to detect significant differences. In this age-range a large variety of pulp configurations (most commonly a separation into mesial and distal pulp compartments) is possible and therefore also a large variety of the volume of dentin (29). It might be possible that, for example very young teeth (<5 years, with a common pulp chamber) do have a different fracture resistance. It would therefore be interesting to examine the effect of the pulpar anatomy of the tooth (and the volume of dentin) on its fracture resistance.

## Does the Presence of a Fissure Influence Fracture Resistance of Equine Cheek Teeth?

The presence of occlusal fissures significantly decreased the ability of cheek teeth to withstand loading forces. This was especially seen for type 1a and 1b fissure in mandibular teeth, and for all fissure types in maxillary teeth. These results support the findings of a longitudinal *in vivo* study, where cheek teeth with fissures were observed to have higher odds to fracture (12). There is a big variation in the occluso-apical depth of fissures, but this did not appear to influence fracture resistance. The observed brown discoloration of fissure fracture walls was demonstrated to be caused by plant material in a histological study (30).

Inconsistent results were recorded for the loading experiments on healthy teeth from the first and second group (**Table 2** vs. **Table 3**). These differences are most-likely attributed to the difference in positioning of the tip of the loading device between groups. This shows that standardization of the experimental set-up is extremely important for future research in order to produce reliable test results. The finding that the mesiodistal length was significant in the mandibular teeth in this study population, but not triadan number (as was the case for the non-fissure model) could also suggest some form of interrelationship between these factors. However, in none of the models where the combined effects of several predictors on fracture resistance were evaluated, these predictors were both significant. Other contributing factors might include spatial variation in dentin and enamel thickness which could influence the fracture resistance in areas relatively close to each other.

## Fracture Level and Exposed Pulp Cavities

Of clinical interest was the significant higher observation of exposed pulp horns when the fracture occurred below and equal to the simulated bone level. This is in agreement with the reported location of the occlusal aspect of the pulp horn, that often lies just beneath the gingival margin (31). These findings suggest that when a fractured equine cheek tooth is diagnosed which involves the intra-alveolar part of the tooth, a thorough examination of the fracture plane is important to verify pulp horn exposure. This inspection should not only be done visually, but also includes probing the entire fracture plane with a sharp instrument (dental explorer/Hedstrom file) since the communication with the pulp cavity can be very small. It is the authors' personal experience that in more chronic cases, careful removal of superficial plaque from the surface is sometimes required before being able to identify pulp exposure. The same procedure accounts for any level of fracture plane as a wide variation in subocclusal secondary dentine thickness has been reported (31–33). In the present study, an exposed pulp horn related to a fracture above the simulated bone level was observed in one case. Age did not have a significant effect on whether a pulp horn became exposed or not in this study population, which is supported by the absence of age-related changes in subocclusal secondary dentine thickness (31, 32). Finally, the presence of an occlusal fissure did not influence the resultant fracture level. However, it was noteworthy that only 1 (out of 42) tooth with a fissure was observed to have an exposed pulp (in contrast to 6/42 teeth without fissures in the matched control group). This might suggest that a fissure-to-fracture evolution is less likely to result in an exposed pulp horn in contrast to a tooth that fractures without the previous presence of a fissure. This might be related to stimulation of the pulp to produce tertiary dentin in the presence of an adjacent fissure. However, due to the relative low number of these observations, it is not possible to draw definite conclusions on this matter.

# CONCLUSION

The methodology used in this study provides an *ex vivo* experimental set-up to test fracture resistance of equine cheek teeth which can be used for future research to examine the potentially weakening effect of dental pathology and to provide an evidence-based approach for their treatment. This study showed that there are anatomical sites of weakness on the tooth. Additionally, it was demonstrated that fissures on the occlusal surface decreased fracture resistance, independently of their depth.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the animal study because The study was performed on material obtained from cadavers of deceased animals (unrelated to this study) and from an abattoir.

## AUTHOR CONTRIBUTIONS

EP, LV, SR, and RC designed the study. EP performed the execution of the study (collecting teeth, preparing teeth, teeth testing and processing data). BB analyzed the data. EP, LV, and BB interpreted the findings. EP and LV prepared the manuscript. All authors contributed to the article and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.699940/full#supplementary-material

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# The Frequency of Communication Between the Synovial Compartments of the Equine Temporomandibular Joint: A Contrast-Enhanced Computed Tomographic Assessment

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**Background:** There is conflicting evidence regarding communication between the two compartments of the equine temporomandibular joint (TMJ). Understanding the inter-relationship between TMJ compartments is critical for diagnostic and clinical management purposes.

**Objective:** To determine the frequency of communication between the discotemporal joint (DTJ) and the discomandibular joint (DMJ) of the equine TMJ in horses free of overt disease.

**Study Design:** A randomized, blinded, controlled cadaveric study.

**Methods:** Equine cadaver heads ($n = 20$), with no reported history of potential TMJ disease, were collected and stored frozen until use. Horses were randomized to the treatment group, such that Group A horses ($n = 10$) underwent arthrocentesis of the left DTJ and the right DMJ compartments, while Group B ($n = 10$) underwent arthrocentesis of the left DMJ and the right DTJ compartments of the TMJ, for a total of 40 joints. Computed tomography (CT) imaging was performed before, and after, intra-articular injection of contrast media in each head. Two observers, blinded to the treatment group, independently interpreted CT images.

**Results:** Communication between synovial compartments occurred in the left TMJ of two horses. Arthroscopic evaluation revealed that both horses had a perforation of the intra-articular disc in the region of the caudomedial fibrous expansion. Mild anterior displacement of the abnormal disc in the joint of one horse was demonstrated using magnetic resonance imaging (MRI).

**Main Limitations:** Sample size, the use of owner provided animals' history, and frozen specimens.

**Conclusions:** No physiological communication was present between the DTJ and the DMJ in the equine TMJ of the cases studied, regardless of which compartment



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underwent arthrocentesis. Two joints had pathological communications. These results suggest that diagnostic, and medical, treatment of intra-articular disease may be most effective when both joint compartments are injected. Furthermore, this study illustrates the value of contrast enhancement while imaging the equine TMJ.

**Keywords: arthrography, computed tomography, magnetic resonance imaging, frequency, disc perforation, internal derangement**

## INTRODUCTION

The equine temporomandibular joint (TMJ) is a diarthrodial joint separated by a bi-concave, fibrocartilaginous, intra-articular disc. The larger of the two joint compartments is bounded by the mandibular fossa of the zygomatic process of the temporal bone dorsally, and the disc ventrally, forming the discotemporal joint (DTJ) (1). The smaller compartment is situated below the disc and dorsal to the condylar process of the mandible, forming the discomandibular joint (DMJ) (2, 3). There is conflicting evidence as to whether there is communication between the two joint compartments. It has been reported that the two compartments do not communicate (2, 4–6). However, one article contradicts this (7).

Primary osteoarthritis of the TMJ is a significant cause of morbidity in a large portion of the human population (8), although it is also described secondary to sepsis (9). Conversely, osteoarthritis of the equine TMJ (TMJ-OA) is most commonly reported to be secondary to joint sepsis (4, 10–13). Primary osteoarthritis with no inciting cause (trauma, sepsis, etc.) has only recently been recognized as an issue in horses where it may incite behavioral changes, poor performance, and colic (14, 15).

The most cost-effective, commonly available, least invasive technique used for the diagnosis and treatment of joint disease is arthrocentesis. The successful treatment of TMJ-OA is predicated on an extensive knowledge of joint anatomy. In humans, it is well established that the intra-articular disc completely separates the two joint compartments of the TMJ (16). This information is lacking in the horse. Therefore, the objective of this study was to assess the frequency of communication between the DTJ and the DMJ of the equine TMJ using computed tomographic arthrography, and if present to further characterize any communication using magnetic resonance imaging and arthroscopy. The hypothesis of this study was that there was no physiological communication between joint compartments in the TMJ.

## MATERIALS AND METHODS

Twenty equine cadaver heads were acquired through donations of horses euthanized for causes unassociated with dental or TMJ diseases (**Table 1**). There were 13 geldings and 7 females, and their age ranged from 2 to 30 years old (mean 18 years, SD ± 7.8). Heads were stored frozen until use. They were thawed by immersing them in running cold water for 36–48 h prior to being utilized, and then an oral speculum was used to open the mouths maximally allowing for subsequent mandibular manipulation. Hair was clipped from the TMJ region of all heads to facilitate accurate identification of the anatomical landmarks. A numbered ear tag was placed on each head that was then randomly assigned to treatment group A or B.

**TABLE 1** | Description of the breeds.

| Breeds | n | % | Mean age | SD | Min | Max |
|---|---|---|---|---|---|---|
| Quarter Horse | 4 | 20 | 16.7 | 10.5 | 2 | 26 |
| Arabian | 3 | 15 | 25.7 | 2.5 | 23 | 28 |
| American Paint | 2 | 10 | 18 | 8.5 | 12 | 24 |
| Suffolk Punch X | 2 | 10 | 16 | 6.5 | 12 | 21 |
| Canadian Warmblood | 2 | 10 | 15 | 11.3 | 7 | 23 |
| Clydesdale | 1 | 5 | 20 | – | – | – |
| Foreign Warmblood | 1 | 5 | 20 | – | – | – |
| Morgan | 1 | 5 | 30 | – | – | – |
| Percheron | 1 | 5 | 12 | – | – | – |
| Quarter Horse X | 1 | 5 | 13 | – | – | – |
| Thoroughbred | 1 | 5 | 5 | – | – | – |
| Westphalian | 1 | 5 | 18 | – | – | – |

Heads were placed in ventral recumbency (on their mandibles), and a baseline CT series was obtained for each horse using a 320-slice computer tomography scanner (Toshiba Aquilion™ One, Otawara, Tochigi, Japan; 135 kVp, 470 mAs, 0-degree pitch using 1 mm slices). After baseline CT, heads in treatment group A ($n = 10$) underwent arthrocentesis of the left DTJ and the right DMJ compartments, while treatment group B ($n = 10$) had arthrocentesis of the left DMJ and the right DTJ compartments using a 22-gauge, 1" needle (5, 7, 17). Needle placement was confirmed by injecting between 2 and 6 ml of tap water to cause palpable and visible distention of each compartment. This was removed and replaced with a 1:1 dilution of the radiopaque contrast solution (Omnipaque, Mississauga, Ontario, CA; 350 mg/ml) with water. The total volume for light breed heads was 3 ml in the DMJ and 4 ml in the DTJ, while 5 and 6 ml, respectively, were used for the draft breed heads. After bilateral injections were completed, manipulation of the mandible through four complete masticatory cycles was performed to distribute the contrast agent throughout the synovial space. CT imaging was then repeated using the baseline protocol. Ultimately, bilateral arthrography studies were completed in each head ($n = 20$), for a total of 40 joints and 80 compartments assessed for communication.

**Abbreviations:** TMJ, temporomandibular joint; DTJ, discotemporal joint; DMJ, discomandibular joint; CT, computed tomography; MRI, magnetic resonance imaging; OA, osteoarthritis; TMJ-OA, temporomandibular joint osteoarthritis.

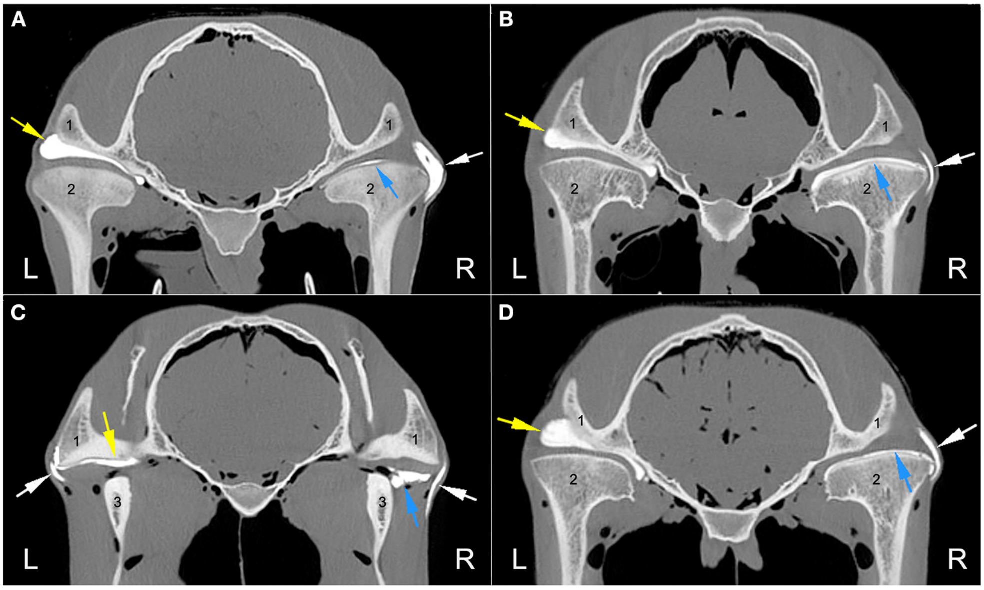


**FIGURE 1 |** Axial computed tomography arthrography images at the level of the temporomandibular joint (TMJ) of four different heads illustrating the varying degrees of contrast extravasation. **(A)** No contrast is present outside of the left TMJ in comparison to the large amount present on the right side. **(B)** No contrast leakage from the left TMJ with mild to moderate amounts present on the right side. **(C)** Mild amount of left TMJ leakage and a mild to moderate amount on the right side. **(D)** No contrast is present outside the left TMJ with mild to moderate amounts on the right side. Arrows indicate the presence of the radiopaque contrast material in the discotemporal joint (yellow), discomandibular joint (blue), and varying amounts outside the joints (white). L, left; R, right. 1, zygomatic process of the temporal bone; 2, mandibular condyle; 3, ramus of the mandible.

The technician obtaining the CT images generated a random case number for each assigned ear tag number. The two investigators determining the presence of joint communication used these case numbers to access the CT images (Horos DICOM viewer, Annapolis, MA, USA) at a later date, such that they were then blinded to the treatment group. Communication was considered present if contrast agent was observed in both compartments of the same TMJ.

Characterization of any communication was performed using magnetic resonance imaging (MRI; Siemens Symphony 1.5 Tesla, Malvern, PA, USA) and arthroscopy. Three-millimeter, transverse and sagittal oblique axial T1 and spin-echo T2-weighted MRI images were obtained with the head in ventral recumbency. Furthermore, arthroscopy of the affected joints was performed using a 2.5-mm 30° arthroscope (ConMed Linvatec, Largo, FL, USA) entering both compartments (2, 5, 17). To visually confirm that the disc perforation allowed passage of joint fluid interchangeably between the DTJ and the DMJ, the arthroscope was placed in one joint compartment, while 1 ml of new methylene blue dye (Omega Laboratories Ltd., Hamon, Montreal, Canada;10 mg/ml) diluted in 6 ml of water was injected into the other compartment. The dye was subsequently removed by thoroughly flushing the joint spaces with 0.9% sodium chloride solution before switching the placement of the arthroscope and needle and repeating the dye instillation. A gross post-mortem examination of the TMJs of heads with disc perforation was performed. Histological examination of both discs of the 26-year-old Arabian horse was examined by a board-certified pathologist using routine H&E staining protocols.

## RESULTS

Arthrocentesis, and subsequent imaging, of all joint compartments was successful. There were varying degrees of extravasation of contrast agent in the majority of horses (**Figure 1**). Communication between compartments occurred in the left TMJ of two 26-year-old (one Arabian and one Quarter Horse) geldings (**Figure 2**). The former horse had the DMJ injected originally, whereas the latter occurred after injection of the DTJ. The oblique sagittal T2-weighted MRI images revealed that the left intra-articular disc was mildly displaced rostrally compared with the right in the Arabian horse (**Figure 3**). No abnormalities were noted in the Quarter Horse.

Bilateral arthroscopy revealed minimal superficial fibrillation of the articular cartilage in the right TMJ of both heads and perforations of the intra-articular discs, with a similar degree of cartilage fibrillation of the left TMJ. The perforation was located in a rostro-caudal orientation in the Arabian head and in a rostro-lateral to caudo-medial orientation in the Quarter Horse head. Both were identified in the caudomedial fibrous expansion of the disc (1). Evaluation of the flow of dye confirmed that the defect had not created a one-way valve effect (**Figure 4**).

Gross post-mortem examination of the TMJs of horses that had disc perforation confirmed the fibrillation of the fibrocartilage of both joint compartments with no apparent difference between the joints with disc perforation and those without. Histological examination of the discs found that the tissue adjacent to the perforation had a higher proportion of poorly staining cells and rare empty lacunae than the same

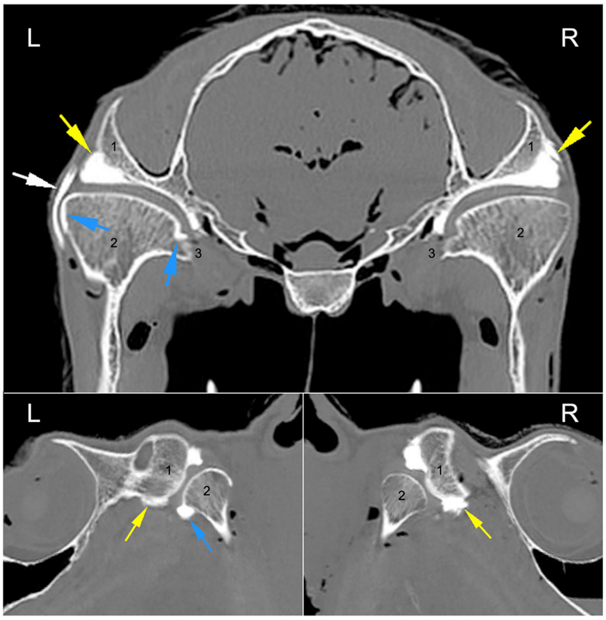


**FIGURE 2 |** Axial and sagittal CT arthrographic images at the level of the TMJ of the 26-year-old Arabian gelding. Arrows indicate the presence of the radiopaque contrast material in the discotemporal joint (yellow), discomandibular joint (blue), and varying amounts in the subcutaneous tissues (white). L, left; R, right. 1, zygomatic process of the temporal bone; 2, mandibular condyle; 3, medial aspect of the mandibular condyle at the insertion of the pterygoid musculature bilaterally.

region of the unaffected disc, which was consistent with necrosis. Additionally, the collagen bundles adjacent to the perforation were frayed, or separated.

## DISCUSSION

The objective of this study was to assess the frequency of communication between the DTJ and the DMJ of the equine TMJ. The results of the study described above confirmed our hypothesis in that there was no communication between the two compartments in normal horses. Our results differ from those of Rosenstein et al. (7) who reported communication between the joint compartments in normal horses. In that report, TMJs were assessed using radiopaque contrast and new methylene blue dye injection. Despite this publication, numerous other publications (2, 4–6, 17), using a variety of different protocols, have not described a communication between the DMJ and the DTJ. Unfortunately, the former authors (7) do not report any further anatomical or histological investigation to determine the cause or location of the communicating channel(s). It is possible that the consistency of the latex material used in some studies (2, 6) relative to that of injectable contrast material led to differing results; however, both Rosenstein et al. (7) and Weller et al. (5) used similar material and reported different results using different imaging methods.

The previously reported morphological variations in the equine DMJ capsule may have represented avenues of joint communication (17). As such, the current study used a 1:1 dilution of the commercial contrast agent with water, reducing the viscosity. The theory was that a less viscous solution would facilitate flow throughout the joint space and pass through any small points of communication. Extravasation of the contrast material occurred in the majority of injected joints (**Figure 1**), demonstrating that this goal had been achieved. Despite filling the injected joints with contrast material, the only TMJs confirmed to have joint compartment communication were those with disc perforations. Extrapolation of our findings to the diagnostic process, and treatment, of equine TMJ disease would suggest that medicating a single compartment may not result in the desired effect. Pharmacologically significant concentrations of injected medication may diffuse across the thin tissue of the intra-articular disc or joint capsule, as occurs in hock and stifle joints of horses (18, 19), but further studies are needed to confirm whether this clinically useful effect occurs in the TMJ.

There are reports of some diseased (septic) equine TMJs having destruction of the intra-articular disc and subsequent communication between compartments (4, 12); however, the authors are only aware of a single previous description of a disc perforation associated with primary osteoarthritis (20). Involvement of the intra-articular disc is common in humans and dogs with TMJ disease (21, 22), where characteristic defects occur in specific locations. In contrast, substantially less is known about the interrelationship between the disc and TMJ-OA in the horse. A recent paper illustrated regional differences in the compressive stiffness of the disc in horses and reported that a decrease in stiffness was associated with joint disease and cartilage erosions on the condylar surfaces of the joint (23). Interestingly, there was superficial fibrillation of the articular cartilage on the condylar surfaces of the TMJs with disc perforation in the current study, but overt erosion was absent. Given a recent finding that 15% of horses had mineralization of the intra-articular disc noted on CT examination (24), it is possible that substantially more horses have clinically silent TMJ disease associated with, or compounded by, disc disease. In the aforementioned study, disc mineralization did not appear to be associated with other abnormalities and seemed to be primarily associated with horse age. While concurrent mineralization and perforation of the intra-articular discs was not noted in the current study, it is interesting to note that disc perforation occurred in older horses. It is possible that age-related changes in the properties of the caudomedial fibrous expansion of the disc predisposed it to perforation, especially given the similar location and positioning of the pathology in both affected horses. Of course, iatrogenic damage may have been a cause of disc perforation especially given that the defects in the equine discs did not look like those classically seen in humans and dogs. Despite this difference, an iatrogenic cause was considered unlikely given the anatomical position and orientation of the perforations, as well as the lack of damage to the articular surfaces. Ultimately given that the authors can only find one picture of disc perforation in primary TMJ-OA in horses, and only two horses in the current study had disc perforation, much more research is needed before any conclusions as to the etiology and consequence of this condition can be extrapolated to the horse population at large.

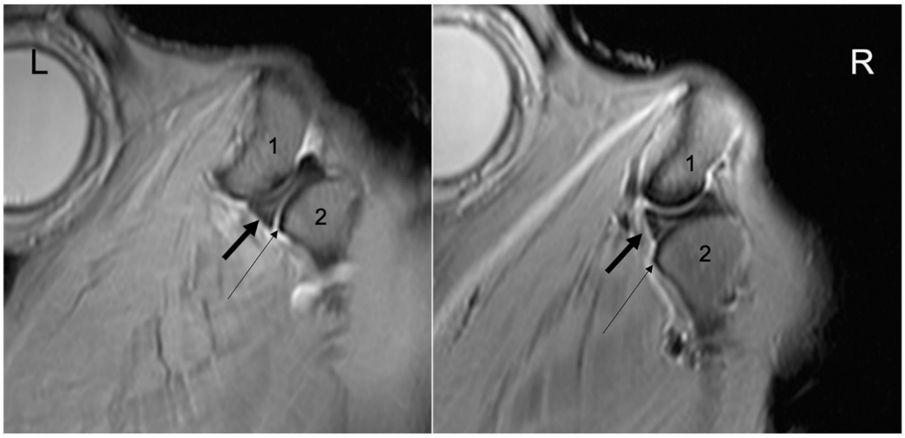


**FIGURE 3 |** Bilateral TMJ oblique sagittal T2*W image of the 26-year-old Arabian gelding indicating mild rostral dislocation of the left intra-articular disc compared to the right. L, left; R, right. 1, temporal bone; 2, mandibular condyle. Note the difference in relative position between the rostral margin of the intra-articular discs (thick black arrow) and the rostral margin of the mandibular condyles (thin arrows).

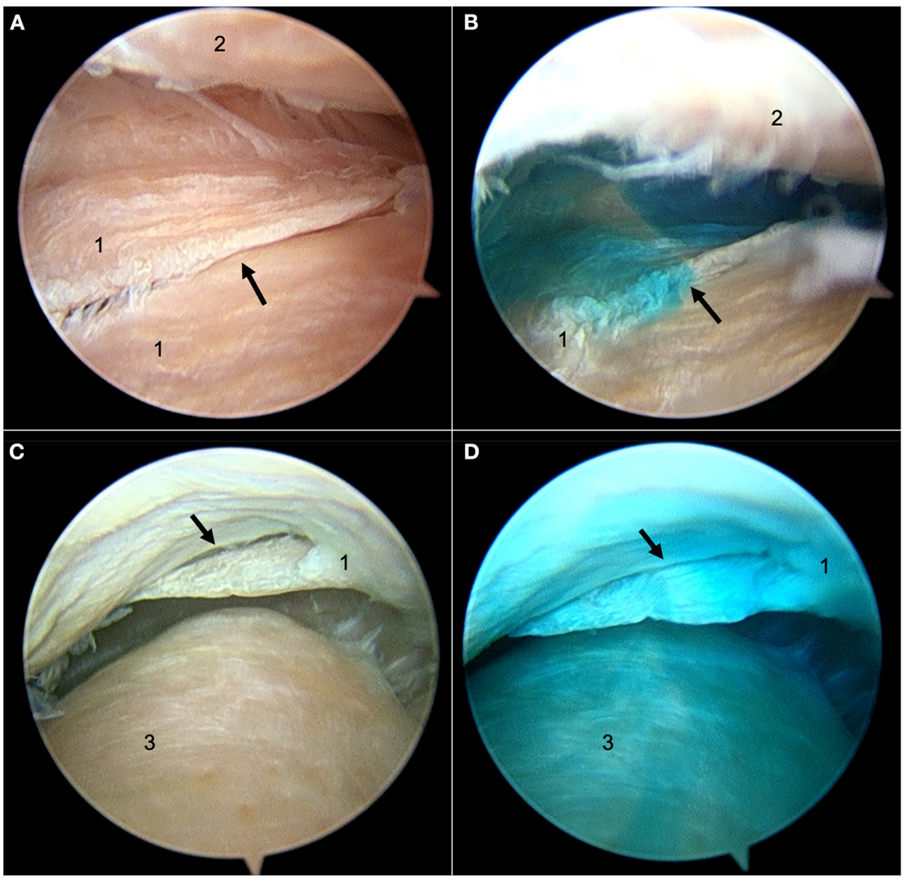


**FIGURE 4 |** Still arthroscopic images from the left TMJ of the 26-year-old Arabian gelding. **(A)** The perforation (black arrow) in the intra-articular disc viewed from the discotemporal joint (DTJ) before new methylene blue dye injection. **(B)** New methylene blue dye passing through the perforation up into the DTJ after being injected into the discomandibular joint (DMJ) below. **(C)** The perforation (black arrow) viewed from the DMJ before dye injection. **(D)** Dye in the DMJ after new methylene blue dye injection into the DTJ. 1, intra-articular disc; 2, articular eminence of the temporal bone; 3, mandibular condyle.

A retrospective assessment of the baseline CT images of the TMJs in which a disc perforation occurred in the current study revealed no apparent abnormality of the disc. It may be that the angle and location of the perforation in these horses precluded identification of the pathology without contrast enhancement. If this is the case, then it is possible that disc perforation occurs more commonly in the horse than is reported, and that the same pathology may have been identified in earlier publications if contrast-enhancement had been part of the standard imaging protocol.

Internal derangement (an abnormal position of the disc) is a common finding in human TMJ-OA (25, 26). In our study, both horses with a perforation of the disc underwent MRI examination and one had a slight rostral dislocation of the perforated left disc when compared to the right. The perforation could not be visualized. It is possible that this small difference is simply normal variation, especially given the orientation of the disc perforation, the fact that there is only a single report describing the MRI anatomy of the equine TMJ (27), and that disc displacement has been reported in up to 35% of asymptomatic human volunteers undergoing MRI of their TMJs (28). However, it may also represent an example of the internal derangement reported in other species. More research is needed to evaluate the normal position of the equine disc using MRI and to further understand the inter-relationship between disc position and joint disease in the horse.

Limitations of the current study include the lack of a clinical history (specifically as it relates to mastication and the TMJ); the lack of an oral examination and assessment of temporal and masseter mass to attempt to quantify the clinical effects of the intra-articular disc perforations; and the use of thawed, previously frozen cadaver heads. However, given that horses with TMJ abnormalities may not show any localizing clinical signs (15, 29), it is possible that the horses with disc pathology had painful, or had altered mastication, which was not appreciated by the caregivers. Furthermore, the objectives of the study were to report on the frequency of TMJ joint compartment communication in our population of horses, and not to determine the effect of that pathology. Finally, while we recognize that using frozen cadaver material is not ideal, the lack of histological difference between the perforated and normal disc suggests that the method of storage did not contribute to the identified pathology.

## CONCLUSION

No physiological communication between joint spaces was present in our population, regardless of which compartment underwent arthrocentesis. Two horses had perforations of the intra-articular disc of the left TMJ resulting in contrast material being present in both joint compartments. Neither of these defects were identified using computed tomography before, or after, contrast enhancement. The presence of the contrast agent in both joints led to further investigation that resulted in the diagnosis. The results of the present study may be extrapolated to suggest that both compartments of the equine TMJ should be medicated, whether for diagnosis or treatment, to deliver the best outcome in clinical cases. Furthermore, advanced imaging without contrast-enhancement may result in an incomplete assessment of the TMJ.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the animal study because the research was performed on cadaver tissues and thus exempt from ethical review and approval.

## AUTHOR CONTRIBUTIONS

KP contributed to the study design and execution, data collection, interpretation and analysis, and manuscript preparation. JC contributed to the study concept, design and execution, data interpretation, and manuscript preparation. Both the authors approved the final manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Long-Term Follow-Up of Restorations of Equine Cheek Teeth Infundibula (2006–2017)

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**Background:** Caries of the infundibula of equine cheek teeth can lead to significant dental disease including increased attritional wear, pulpar and apical disease, secondary sinusitis, and dental fracture. Restorations of cavities of equine cheek teeth infundibula have been performed since 1889. Recent advances in dental materials, instrumentation, and techniques have facilitated the use of dental restoration techniques by equine veterinary practitioners. No studies to date have demonstrated the safety or efficacy of restorations of equine cheek teeth infundibula.

**Objectives:** To assess the long-term results of restorations of equine cheek teeth affected by infundibular caries, to report on the safety of the procedure, and to give guidelines for future restorative therapies.

**Study Design:** Retrospective analysis of results of clinical and oroscopic examination of horses that underwent infundibular restoration procedures between 2006 and 2017.

**Methods:** A total of 223 infundibula in 185 maxillary cheek teeth in 92 horses were restored using a variety of dental materials including glass ionomer cement, flowable and compactible resin composites. The time between restoration and re-examination was recorded along with findings of clinical signs in the interim, restorative material loss, and any further pathological changes of the teeth including caries progression, fracture, or apical disease. Follow-up examinations were performed over two study periods 2006–2012 and in 2017.

**Results:** Over the full study period, 99% of treated horses available for follow-up examinations had no adverse clinical signs or developed any abnormalities of restored teeth observable on oroscopic examination. Of horses re-examined, 83% of restorations were shown to have minimal or no loss of the restoration material, with occlusal surface wear visibly comparable to other adjacent maxillary teeth. Statistical analysis showed success of the procedure was related to the restorative material used, the restoration technique, and the caries grade present at the time of restoration (grade 3 is more successful than grade 2).

**Main Limitations:** There are no case controls in this study and therefore it is not clear if restoration of equine infundibula is a consistently beneficial procedure, or at which grade of caries progression restorations should be performed for optimum benefit. The procedures were not re-examined at consistent regular times creating some difficulties



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*Pearce CJ and Brooks N (2022) Long-Term Follow-Up of Restorations of Equine Cheek Teeth Infundibula (2006–2017). Front. Vet. Sci. 8:793631. doi: 10.3389/fvets.2021.793631*

in standardizing results. Re-examinations of treated horses did not consistently include radiography or computed tomography and therefore some apical changes may have occurred in treated teeth without visual oroscopic or external clinical signs.

**Conclusion:** Restoration of equine infundibula using materials developed for human dentistry including flowable resin composites is a safe and long-lasting procedure and appears to prevent the development of further pathological changes including apical infection and dental fracture.

**Keywords: infundibulum, infundibula, restoration, hypocementosis, caries**

## INTRODUCTION

The equine dental infundibulum (plural: infundibula) is anatomically an invagination of the dental enamel from the occlusal surface in an apical direction that is present in incisors ($n = 1$) and maxillary cheek teeth ($n = 2$) (1). The vascular supply to the developing infundibulum is from its occlusal aspect, through the central infundibular artery, and via small side vessels mesially and distally (2). The infundibula of erupted cheek teeth are technically inert, although the lateral vascular supply usually survives for a short time (months to years) post eruption (3, 4). Abnormalities of the infundibula of maxillary cheek teeth include developmental and acquired disorders (5), the most common being variable degrees of infundibular hypocementosis (IH) (2, 4, 6) and infundibular caries (IC) (5, 7–12). Infundibular hypocementosis most commonly affects the apical aspect of the infundibulum although rarely there may be more complete or even total absence of cementum (4, 13). Prevalence of infundibular abnormalities has been shown to be up to 90% in anatomical (14), clinical (15), and computed tomographic (CT) (4, 5) studies. In one study 90% of teeth showed significant infundibular changes on combined occlusal surface and CT examination (16). Another study showed a similar prevalence with only 11.7% of infundibula of clinically normal horses completely filled with normal appearing cementum on CT examination (4). Other earlier studies also described similar ranges of prevalence of infundibular disorders (17, 18). Dental caries has been defined as a progressive acidic demineralization of the inorganic matrix of dental tissues secondary to bacterial fermentation of carbohydrate substrate and subsequent organic matrix loss (19, 20). A likely etiology is that exposure of IH lesions occlusally through normal physiological dental eruption and attrition results in impaction of food ingesta into the exposed infundibular defects, resulting in secondary caries (**Figure 1**) (11, 12, 21–23). In Sweden infundibular caries of the Triadan 106/206 positions were found to be strongly associated with the presence of a novel bacteria (*Streptococcus devreisei*) isolated from caries lesions (20). Subsequent molecular bacteriology has shown hundreds of bacterial species including Streptococci to be present in dental disease, but their individual roles are difficult to elucidate (24).


**FIGURE 1 |** Oroscopic image of Grade 3 mesial infundibular caries of a Triadan 109 tooth at presentation.

Infundibular caries appears to be variably progressive, depending on the extent and the site of the IH lesion and thus the age of occlusal exposure of the infundibular defect. Potential sequelae include increased occlusal attrition (22), pulpitis and apical infection (13), and dental fracture (10, 13, 17). Increased attrition is considered due to loss of infundibular cementum and most importantly enamel. Microbial invasion from the carious infundibulum to the dentine-pulp complex is the likely cause of apical infection (3, 13, 25). One study showed caries from the infundibulum caused apical sepsis in 16% of maxillary cheek tooth apical infections (13); however, this has subsequently been suggested to be an underestimate (3). Advanced lesions of both mesial and distal infundibula, especially those that coalesce, are likely to result in significant structural weakness of the tooth (12, 26). Infundibular caries related dental fracture is assumed to be due to IC providing a central plane of structural weakness in the tooth thus predisposing it to pathological fracture when exposed to the normal forces of mastication (27). Studies have repeatedly demonstrated that the maxillary Triadan 09 position is most commonly affected by infundibular hypocementosis, caries, and secondary associated sequelae (4, 10, 13, 15, 17, 18, 28, 29). One study found caries affecting the full length of the infundibulum in 8.2% of infundibula studied, most commonly in the 12–20-year age group, and with the average depth of 35 mm in carious infundibula (4).

The principles of dental restoration are to "protect the pulp, arrest decay, restore the tooth to function, and prevent further disease" (30). Restorations of human teeth dates to Neolithic times (31) with the practice becoming widespread through the late 19th century (32). Documentation of equine dental infundibular restorations is sparse but dates to 1889 (33, 34).

## METHODS

Teeth that had undergone infundibular restorations by the author between 2006 and 2012 were re-examined clinically and oroscopically during this period, and then again during 2017. All oroscopic examinations were performed under standing sedation with video recordings of treated teeth.

### Case Selection for Infundibular Restoration

Teeth were selected for restoration during examinations at routine or referral dental appointments. Grading of infundibular caries was performed using a classification system modified from an original system by Honma (35). The grading system used is outlined below:

Grade 1—Caries of infundibular cementum only.
Grade 2—Caries of infundibular cementum and enamel.
Grade 3—Caries of infundibular cementum, enamel, and dentine.
Grade 4—Caries of mesial and distal infundibula with coalescence.
Grade 5—Infundibular associated dental fracture, apical disease, or tooth loss.

At the initial examination, teeth considered potentially suitable for restoration were assessed oroscopically using the following selection criteria and using the above grading system:

1. Grade 3 infundibular caries with a minimum infundibular defect depth of 10 mm (**Figure 1**) or,
2. Grade 2 infundibular caries if contralateral to a tooth with grade 5 infundibular caries, minimum infundibular defect depth 10 mm and,
3. Absence of clinical evidence of pulpar disease of the selected tooth, or of ipsilateral sinusitis or a history of ipsilateral nasal discharge or malodor.

Initially, all cases had routine radiography of their maxillary cheek teeth. However, after ∼50 cases, radiography was only utilised for horses that presented with or had a history of ipsilateral nasal discharge or had teeth that had clinical evidence of pulp involvement oroscopically (secondary dentine defects, fractures, gingival draining tracts, or focal gingival recession). Teeth with these changes were not selected for restoration.

### Restoration Procedure

All procedures were performed under standing sedation and oroscopic guidance. A pneumatic high speed, water irrigated turbine handpiece, with handpiece extensions for equine use, various burrs, and a 90-degree high pressure air and water wand were used for all cavity preparations (Equine Perio-unit, Veterinary Dental Products, Wisconsin). During the 6 years (2006–2012) of the first follow-up period, small alterations to the technique were made as the author became more experienced with the equipment and procedure, along with input from human dentists and veterinary dental specialists. A summary of the technique is outlined below:

1. Impacted food was removed from the occlusal aspect of infundibular cavities (defects) using a sharp occlusal probe or K-flex file (Sybron Endo, CA) held in hemostats.
2. Deeper impacted food and carious cementum or dentine was removed as far apically as possible using burrs and a high-speed dental handpiece, under continuous or intermittent oroscopic guidance. Burr types and sizes ranged from surgical length (29 mm) no. 8 round carbide or diamond burs, cylindrical diamond burs (29 mm) to surgical taper fissure burs (31 mm). In some cases, a slow-speed handpiece with a 15 mm right-angle (RA) to friction grip (FG) mandrel adaptor (Premium Plus UK Ltd, Dorset, England) was used, using one of the FG burs above, thus increasing the total burr length up to 45 mm.
3. Any remaining deeply impacted food material and debris was manually removed from the infundibular apex using K-flex files and Hedstrom files (60 mm, Dr Shipps, USA). A carbamide peroxide-EDTA file lubricant gel (Canal Plus, Septodont, UK) was used to coat the file or was injected apically into the infundibulum to aid the debridement procedure.
4. The cavity was flushed with high pressure air and water to remove the loosened products of the above debridement (in cases where patency of the infundibular apex was not suspected).
5. The infundibular cavity was inspected oroscopically, and Steps 2–4 were repeated until the cavity walls and the infundibular apex were visually clear of all debris and carious material as far as was possible. The cavity was recorded as fully debrided when the apex and walls were clearly visible with no remaining impacted food or discolored cementum remaining (**Figure 2**), or as not fully debrided, if some such inaccessible material remained prior to restoration.
6. The cavity was then flushed with 4.5% NaOCl, 2% chlorhexidine, or water (details recorded), rinsed with water, and air dried.
7. A single-etch bonding product was applied thinly to the cavity walls (Adper Prompt L-Pop, 3M), thinned with air (to distribute it more evenly and avoid clumping of liquid), and then light cured for 20 s.
8. The cavity restoration was performed (under oroscopic control) using a variety of materials and techniques:

    a. Glass ionomer cement applied manually and compacted using a metal compactor and burnisher (Fuji IX, GC, Tokyo, Japan).
    b. Compactible composite applied as above (XOP, R&S Dental, Paris, France).
    c. Dual-cured flowable resin composite (Starfill, Danville, USA) placed either in an incrementally layered filling

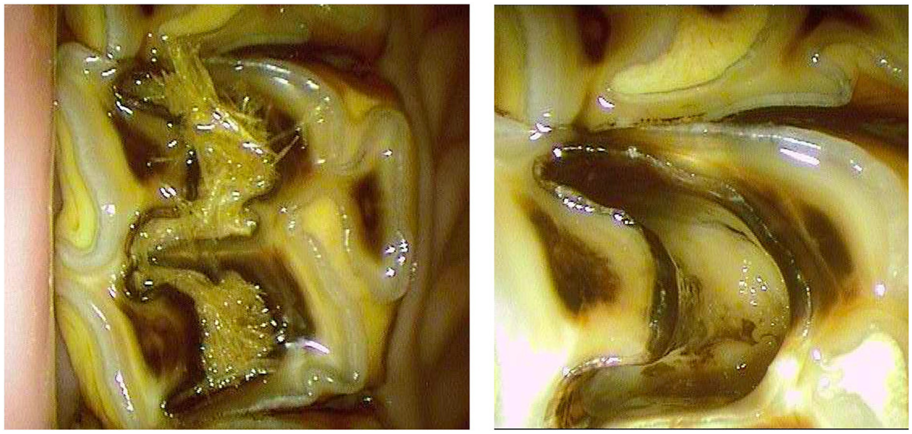

**FIGURE 2 |** Oroscopic image showing preparation of mesial and distal infundibula of a Triadan 109 tooth prior to restoration. *Left*, before and *Right* after successful cavity preparation.

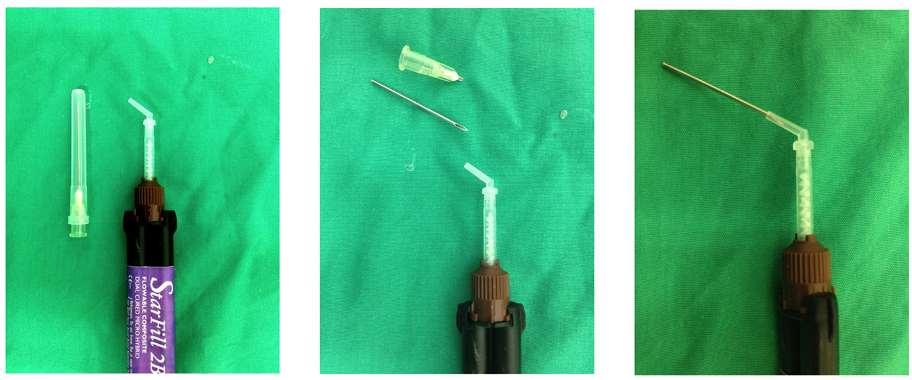

**FIGURE 3 |** Method used to fabricate mixing tip extensions using a 19G 3.8 cm hypodermic needle.

technique (see below), or bulk filled without any light cure, using a 19G 38 mm needle tips reversed and inserted into the mixing tip (**Figure 3**).

d. Combinations of the above (compactible composite used as a base liner, followed by occlusal flowable resin composite).

## Flowable Composite Application Techniques

Flowable resin composite restorative material (dual-cured) was placed either using a modified oblique incremental layered technique based on a human technique (36) or as a bulk fill. For the incremental layered technique, material was placed from the apical aspect occlusally, in 3–4 layers, filling the narrowest parts of the cavity first, usually the infundibular buccal infoldings. This was to utilise the increased surface tension of placing a viscous liquid material in the narrow margins of the cavity, to avoid gravitational slumping (flow ventrally). A further 2–3 layers were then applied in the central region of the defect, working occlusally. A short light cure was occasionally required to prevent occlusal gravitational flow of the material. For bulk fill restorations, the material was simply extruded in an apical to occlusal direction, starting centrally and filling the entire cavity continuously, while moving the needle tip in short, rapid occlusal to apical motions to help drive the material into the narrow margins of the cavity. No light cure was applied for bulk fill restorations.

All restorations were performed at a single session. Referral cases were only included in the study if the first author was able to personally re-examine the cases. Cases were re-examined oroscopically at varying time intervals following treatment over a 6-year period (2006–2012) and those available for further follow-up were subsequently re-examined during 2017. For the first dataset (2006–2012) results were collated and analysed statistically. For the second data set, the occlusal oroscopic appearance of the restoration was recorded but no statistical analysis of results was performed due to the large number of cases lost to follow-up.

## Statistical Analysis

Data from the first period of follow-up was statistically analysed using Pearson chi-square to test for independence between sets of two variables; the *P*-value was set at 0.05 or less when the

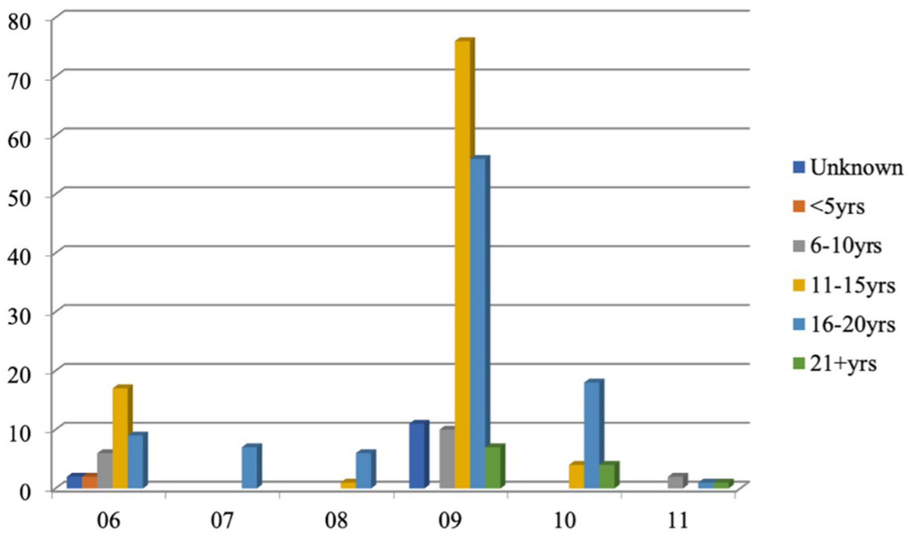


**FIGURE 4 |** Number of teeth by Triadan position and ages of horses (years) with infundibular caries lesions selected for restoration (left and right sides combined).

null hypothesis that the variables were independent of each other could be rejected, demonstrating that the variables were related. Success was defined as the tooth still present and with more than 90% of restorative material remaining occlusally at oroscopic examination, no fracture of the tooth, no immediate evidence of complications related to the procedure, and no clinical signs of dental disease (sinusitis, facial swelling, dysmastication) since treatment.

Statistical analyses examined the success of the procedure in relation to Triadan number, age of horse, grade of infundibular caries prior to restoration, restorative material used, mesial vs. distal infundibulum, restoration technique (incremental layered restoration vs. bulk fill), and whether the infundibular apex was completely debrided prior to restoration.

## RESULTS

A total of 223 infundibula in 185 teeth from 92 horses met the selection criteria and were restored. The mean age of these horses was 14.7 years (range 6–25 years). The number of teeth selected for restoration was similar for the left and right sides. The frequencies of combined left and right Triadan positions and horse age are shown in **Figure 4**. The Triadan 09 position was the most commonly treated position representing 66.7% of teeth treated; the 06s (15.3) and 10s (10.4%) were the next most commonly treated positions, followed by a very low percentage of 08s (3.2), 07s (3.2), and 11s (1.4%).

Overall, 63% of infundibula selected for restoration were mesial, 5% the distal infundibulum only, 25% mesial and distal infundibula (in the same tooth), and 7% with coalescence of mesial and distal infundibula (grade 4). The grade of infundibular caries selected for treatment was most commonly grade 3, in the maxillary 09 and 06 positions, with the most common grades vs. ages displayed in **Table 1**.

**TABLE 1 |** Most common grades of infundibular caries (IC) and Triadan positions of teeth restored and age groups of treated horses.

| Age group (years) | Number of restorations | Percentage of all treated cases | Most treated triadan position | Most common grade of IC treated |
|---|---|---|---|---|
| 0–5 | 2 | 0.89 | 06 | 2 |
| 6–10 | 20 | 9.38 | 06, 09 | 3 |
| 11–15 | 90 | 40.18 | 09 | 3 |
| 16–20 | 91 | 40.63 | 09 | 3 |
| 20+ | 9 | 4.02 | 09 | 3 |
| Age unknown | 11 | 4.91 | 09 | 2, 3 |

**TABLE 2 |** Frequencies of materials used for infundibular restorations.

| Restorative material | Number of procedures | Percentage of procedures |
|---|---|---|
| Starfill resin composite | 150 | 67% |
| XOP compactible composite | 9 | 4% |
| XOP (base) + Starfill (occlusal) | 41 | 18% |
| Fuji IX (base) + Starfill (occlusal) | 9 | 4% |
| Others | 14 | 7% |

The most common material used for restoration was a flowable, dual-cured resin composite (Starfill, Danville, USA) placed directly using either an incremental layered technique (80% of procedures) or a direct bulk fill (10%). **Table 2** shows the frequency of materials used.

Horses were re-examined in two separate periods of follow-up. The initial follow-up period was between 2006 and 2012, with

**FIGURE 5 |** Oroscopic image of the mesial infundibulum of a Triadan 109 tooth, 2 years post-restoration.

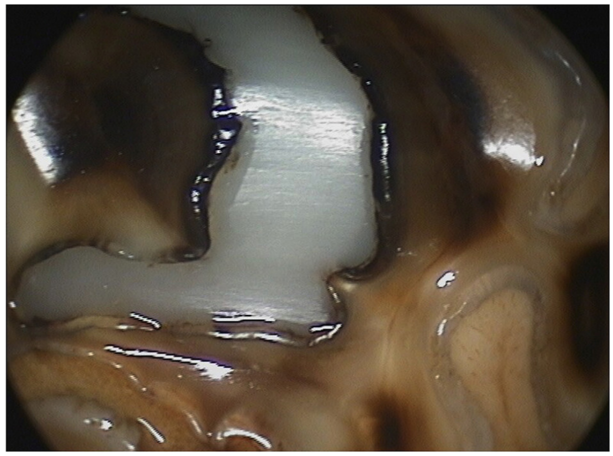

**FIGURE 6 |** Close up oroscopic images of a Triadan 109 tooth 2 years post-restoration (same tooth as **Figure 5**). Attritional wear lines can be seen through the restorative material.

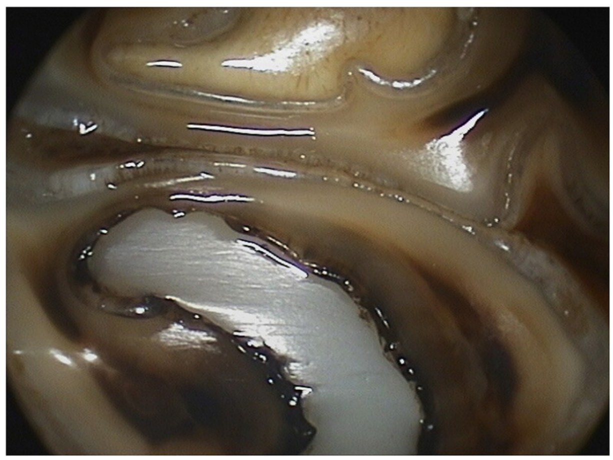

**FIGURE 7 |** Close up oroscopic images of a Triadan 109 tooth 2 years post-restoration (same tooth as **Figure 5**). Attritional wear lines can be seen through the restorative material.

the mean follow-up time during this period being 28 months (range 2–72 months). A further follow-up study was performed in 2017 (mean follow-up time 78 months, range 60–120 months).

Over the initial study period, 90/92 horses (97%) developed no apparent post-restoration complications in the treated teeth. Two horses developed apical infection post-restoration (one tooth each) and these teeth were subsequently extracted. Restorations were documented to be successful (complete restorations present or <10% of restorative material absent occlusally, with no deterioration of infundibular caries grade) in 193/225 restorations (86%), in 77 horses (83%), with normal occlusal surface wear of the treated teeth, including differential wear of enamel and the restorative material present at re-examination (**Figures 5–9**). Twenty restorations (10.8% of procedures) from 10 horses had restorations with partial or complete loss, or absence of restorative material (categorized as failures) at re-examination, and in all cases the restoration was replaced as the teeth were still considered vital (**Figure 10**). Partial crown fractures involving one infundibulum were identified in 6 teeth (3%) prior to restoration with no further fracture later recorded after restoration. Iatrogenic pulp exposure during cavity preparation was identified in one horse that did not receive any specific pulp therapy and without any recorded later complications. Twelve horses (13%) were initially referred for extraction of teeth with infundibular caries related fractures, with other teeth in these horses selected for restorations (25 teeth in total). None of the 25 restored teeth with infundibular restorations had progressed to fracture at the time of follow-up (mean follow-up time 39 months) and with 3/25 teeth (12%) having partial loss of restorative. Four horses (4.3%) with teeth selected for restorations had other teeth identified as having concurrent Grade 1 or 2 lesions which were not restored but which subsequently fractured, with no progression of caries grade or dental fracture occurring in the restored teeth.

From this first study period, statistical analysis was performed on 160 restored teeth for which full data was available (SPSS statistical analysis software, IBM). Results of Pearson chi-squared analysis showed that success was either related to or independent of several factors. Compactible chemical cured composite ("XOP"), compactible glass ionomer cement ("Fuji IX"), and combinations of products had a lower success rate compared to flowable dual cured composite (Starfill) ($P < 0.0005$, 6 d.f). Infundibular caries grade was found to be significant, with grade 2 lesions having a higher failure rate than grade 3 ($P < 0.005$, 4 d.f.). The Triadan position of the restored tooth, the age of the horse, and the site of infundibulum restored (mesial vs. distal) were not related to success ($P > 0.25$). The degree of apical debridement (complete vs. incomplete) was also not found to be related to success ($P = 0.1$, 1d.f).

Out of 92 horses treated initially, 36 teeth in 22 horses were available for a second follow up after a further 5 years (range

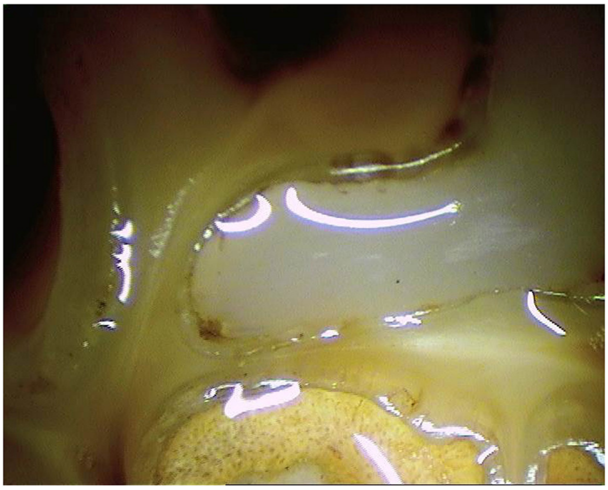

**FIGURE 8 |** Oroscopic image of the distal buccal infolding of the mesial infundibulum of a Triadan 109 tooth 15 months post-restoration.

60–120 months from initial treatment, mean 78 months). The age range of the horses at this follow-up was 13–27 years, mean age 24 years 4 months. All the 36 treated teeth examined at this stage were present (100%) but one tooth that had been restored 10 years previously now had a midline sagittal fracture. Of the 35 complete teeth, 15 had loss of their infundibula and senile excavation ("cupped" occlusal surfaces) with no filling material (or infundibula) visible. Filling material was still visible in 19 teeth (54% of all teeth, 95% of teeth with infundibula) with 11 teeth (58% of teeth with infundibula) still having complete restorations present on their occlusal surface (**Figure 11**). Small (1–2 mm) defects containing food material were present at the edges of restorations in seven teeth (37%) (**Figure 12**). One restoration had no filling material visible, with food material present within the restored infundibulum and an occlusal exposure of pulp horn three. Teeth other than those restored were absent from three horses having fractured due to midline infundibular caries-related sagittal fractures according to the clinical histories.

## DISCUSSION

Infundibular restoration was shown in this study to be a safe technique, with minimal complications recorded post-treatment over a prolonged period. A limitation of the study is that the data does not report the likely outcome had these teeth not been restored, but it appears likely that in the restored teeth the caries was arrested, as almost all the teeth remained structurally sound. Additionally, only 2/160 (0.13%) teeth that were re-examined developed pulp or apical disease as assessed from oroscopic and clinical examinations. Considering the time scale for the follow up examinations (up to 11 years following treatment for the second follow up) it is likely that had there been pulp disease, gross clinical signs, secondary dentine pulp defects, or gingival discharging tracts would have been identified in at least some cases. In two teeth from horses from the second data set that had a single infundibulum restored, secondary dentine defects were observed in these restored teeth, but the affected pulp canals were not adjacent to the restored infundibula, but adjacent to the other carious infundibula that were not restored (did not initially meet the selection criteria). This may suggest that restoration adequately protects the pulp; however, the results are not conclusive due to the low numbers of secondary dentine defects identified in unrestored teeth.

The selection criteria used most frequently selected the mesial infundibulum of Triadan 09 teeth from horses with a mean age of 14.5 years (range 6–25 years). This is consistent with other studies of the prevalence of larger infundibular hypocementosis defects (2, 4, 5, 16) in relation to the expected age of exposure of apical hypocementosis lesions through eruption and attrition, and documented studies of occlusal infundibular caries (7, 15, 24). The cases selected for restoration also share the same age and Triadan position as found in studies of maxillary cheek teeth with fractures and/or apical disease (13, 37, 38). It is not statistically evident from this study that these variables are related, or that restoration of infundibula of these teeth definitively protects them from future infundibular disease. However, studies have shown that infundibular hypoplasia and secondary caries is responsible for apical disease in a significant number of teeth (3). It seems likely as proposed previously, that apical infundibular hypocementosis lesions, described as a developmental malformation of infundibula (3), become more prone to cause caries once these lesions are exposed occlusally (3, 13, 17). If restoration is a safe procedure in the long term, as this study shows, then prevention of food impaction into these defects, thus preventing further caries should protect the endodontic system post-restoration. The results showed that out of all the teeth restored and re-examined later (even up to 11 years later), only 1/185 restored teeth subsequently developed a mid-sagittal infundibular related fracture. There are no controls in this study so it cannot be proven that restorations of carious infundibula prevent fractures, but considering the age range and Triadan number, and advanced caries grades of the restored teeth, these teeth being the most associated with fracture and often complicated extractions (38) it is plausible to consider that restoration provides structural stability to the tooth long term.

The effectiveness of different materials used to restore teeth was shown to vary, with flowable resin composite placed using an incremental layering technique being the most successful. This may be in part due to the operator performing this technique most frequently and therefore developing better material handling skills. It may also be due to the material itself, with consistent observation of this material oroscopically flowing into the infundibular recesses, resulting in a more complete filling and bonding of the restoration material to the infundibular walls. Compactible materials used in human dentistry frequently rely on undercuts to retain them which were not used in these cases, and it is possible that poor compaction technique resulted in less than adequate bonding to the cavity walls in this study.

Documentation of long-term cheek tooth wear with infundibular composite restorations in this study shows that the resin composite used wears down at similar rates to the surrounding dentine, with enamel wearing more slowly than

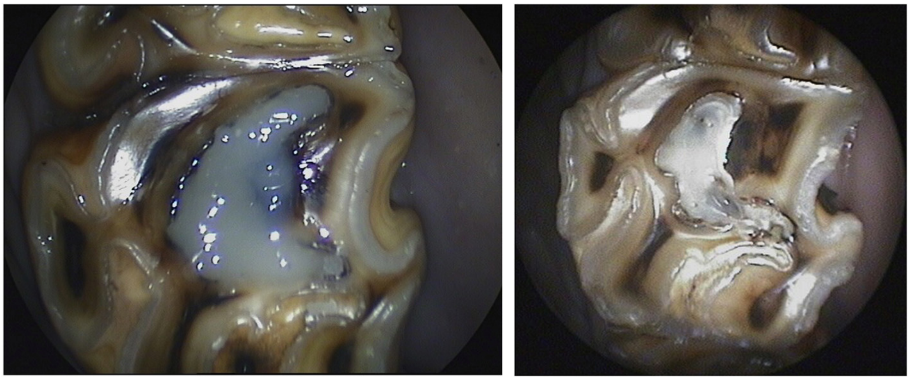

**FIGURE 9 |** Oroscopic images of a Triadan 209 immediately after (left) and 2 years 4 months after (right) infundibular restoration.

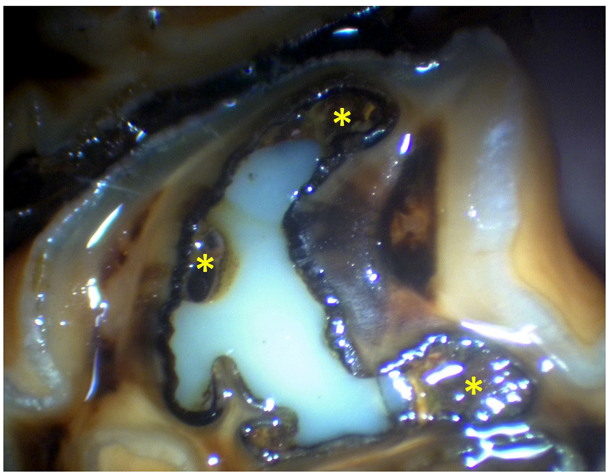

**FIGURE 10 |** Oroscopic image of the mesial infundibulum of a Triadan 209 4 years 3 months post-restoration of the mesial infundibulum, showing some defects in the restoration (*).

**FIGURE 11 |** Oroscopic image of a Triadan 209 tooth 10 years post-restoration of the mesial infundibulum.

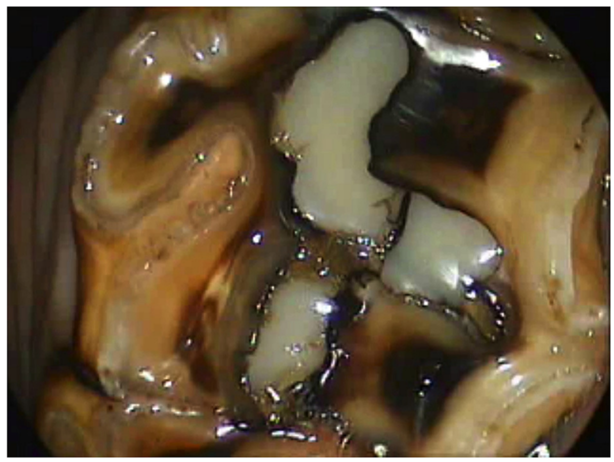

**FIGURE 12 |** Oroscopic image of a Triadan 209 tooth 9 years post-restoration of the mesial infundibulum.

the composite, resulting in enamel ridges protruding slightly from the surface (**Figures 5–9**). This may be due to the resin composite chosen being a posterior restorative or core build-up material and not generally suitable for human dental crown replacement that requires higher wear resistance. Meta-analysis of studies into longevity of posterior resin composite restorations in humans has shown a mean failure rate of 1.6–4.1% (39), lower than reported in this study. However, direct comparisons to human restorations are difficult due to the huge differences in the cavity sizes in horses compared to humans, infundibular vs. pulp cavity restorations, and the material bonded to (dentine in humans vs. enamel, cementum or occasionally dentine in horses). Also, the human studies generally had different criteria for success to this study, with failures including the later development of dental fracture, progressive caries, or endodontic disease. Using these criteria, our results are easily comparable considering so few of the teeth restored in this study progressed to fracture or endodontic disease. This meta-analysis of human composite restorations (39) also showed that there was a marked increase in failure rate for each extra surface of the restoration exposed orally. Equine infundibular restorations are usually deep intra-coronal restorations, with most of the surface area of the filling bonded to the surrounding tooth, and only a small surface area of the restoration exposed occlusally, therefore having a higher retention rate.

The success of restorations vs. infundibular caries grade at the time of restoration was shown to be higher with grade 3 caries compared to grade 2. This was contradictory to the expected outcome that larger cavities (grade 3) would have greater restoration material loss. The results may be due to the material that the restorative is bonded to, the age of the horse, and therefore the depths of the cavities, or other factors. The single etch product used almost exclusively for these cases is particularly suited to enamel and dentine bonding, but not for cemental bonding, more likely to be employed in cases of grade 2 caries where more infundibulum cementum is present. The open structure of cementum compared to enamel or dentine may collapse when a strong acid etch is used (as for the single etch product used) resulting in bond failure. This is reported in human dentistry, with both single etch adhesive systems and total etch systems being reported to have significantly lower bond strengths to cementum compared to dentine (40). There was no statistical analysis of other factors relating to this and therefore there may be unrecognized factors involved such as the age of the horse and the size of restored infundibula. In some cases, restorations classified as failures were initially considered to be caused by loss of restorative material. However, on re-examination of the original oroscopic images prior to restoration, it is likely instead that some of these were areas of cementum that were not debrided, particularly at the margins of the buccal and the palatal infoldings, which subsequently developed caries when exposed occlusally (**Figure 10**). In a future development of the technique, the author has made more effort to remove these areas of cementum.

The outcome of infundibular restoration was not statistically linked to the degree of debridement of the apex immediately prior to restoration. This was not as expected, following the assumption that a dental cavity must always be completely clean and free of foreign material for a successful restoration. In preparing these cavities, a 32 mm high speed water irrigated surgical fissure bur was always used to carefully debride the walls of the cavities under oroscopic guidance, followed by manual instrumentation of the more apical aspects, always using a disinfectant lubricant gel. Considerable effort was always made to achieve a fully debrided apex devoid of all impacted food and carious cementum. In some instances, however, it either became too time consuming, or the apical discoloration noted oroscopically was assumed to be cementum that was firmly adhered to the apical enamel and drilling it away with a longer bur may have risked penetration of the apex and exposing pulp, as occurred in one case. In these instances, the cavity was flushed with disinfectant (4.5% NaOCl) before restoration. Reasons for the results showing no difference in outcome could have been the chemical sterilization in the apical region, or the creation of a bacteria-tight seal by adequately preparing the cavity walls to a depth of around 30 mm, using a strong bond effective for enamel, preventing any carbohydrate substrate reaching the apical region. Any viable bacteria present in organic matter trapped apically would be entombed and likely to remain dormant, unable to multiply or cause dental tissue erosion through caries without a supply of carbohydrate from the occlusal aspect. This is presumably why the very high prevalence of apical infundibular hypocementosis with little or no occlusal communication is generally considered little more than an incidental finding, and why infundibular lesions with apical enlargement and significant occlusal communication (16) can lead to progressive and serious caries (3, 25). In subsequent developments of the technique of infundibular restoration, the author has used a two-stage endodontic style technique utilizing calcium hydroxide paste for a temporary period to disinfect and clean the apical regions in such cases more effectively (T. Lundstrom, personal communication) (41).

In summary, intra-coronal direct restoration of carious infundibula using a flowable dual-cured resin composite, bonded using the single etch process, was shown to be a safe long-term procedure with minimal loss of restorative material, and minimal clinical disease of treated teeth. The case selection criteria used in this study selected teeth that have been shown in other studies to be high risk for fracture and apical disease, and restorations of these infundibula may prevent these possible pathological sequelae. Further controlled studies, and studies using ancillary imaging modalities such as radiography and computed tomography of restored teeth will help to further qualify the safety and efficacy of this procedure.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the animal study because the horses in this study underwent clinical procedures that make up part of standard clinical practice and no procedures were performed that were not considered necessary or ethical. Written informed consent for participation was not obtained from the owners because the clients / owners of these horses signed consent forms for the procedures which were performed as part of clinical practice.

## AUTHOR CONTRIBUTIONS

CP was the primary author who selected the clinical cases, performed the clinical procedures, and wrote the manuscript. NB performed the follow-up of the second case series in 2018 recording the cases oroscopically and collated the data. All authors contributed to the article and approved the submitted version.

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# Studies on Age-Related Changes in Equine Cheek Teeth Angulation and Dental Drift

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**Background:** Cheek teeth (second through fourth premolars and first through third molars) diastema is a common and painful equine disorder caused by the absence of effective tight interdental contact between these teeth. Limited objective information is available on the angulation of equine cheek teeth that control dental drift or on mesial or distal equine cheek teeth drift that should normally prevent this disorder.

**Objectives:** To measure the angulation of the mesial and distal cheek teeth in horses of different ages, quantify age-related cheek teeth mesial and distal dental drift, and measure the cheek teeth row length in horses of different ages.

**Study Design:** Retrospective review of computed tomographic images of equine heads.

**Methods:** Case details and CT images from clinical equine cases that had undergone standing CT head examination were collated.

Three sets of measurements were acquired from each head. "Head size" calculated as the distance between the caudal aspect of the orbit and the caudal aspect of the naso-incisive notch was used to standardize measurements in different sized heads. The length of the cheek teeth rows measured from the mesial aspect of the Triadan 06 occlusal surface to the distal aspect of the Triadan 11 occlusal surface. The rostro-caudal (antero-posterior) position and angulation of the mandibular and maxillary Triadan 06 and 11 teeth were measured in relation to reference lines drawn on CT images.

**Results:** Significant mesial drift occurred in the maxillary and mandibular Triadan 11s. Despite their distal angulation, the upper and lower Triadan 06s also drifted mesially. The mean angulation of Triadan 06 and 11 mandibular teeth (17.8 and 26.2°, respectively) was almost double that of maxillary teeth (9.2 and 13.3°, respectively) with both Triadan 11s having greater angulation than the 06s. Cheek teeth angulation only significantly decreased in the mandibular 06s. Cheek teeth arcade lengths decreased with age, but these decreases were not significant.

**Main Limitations:** Limitations include the relatively small sample size.

**Conclusions:** In the population of horses used for this study, age related mesial drift occurred in both Triadan 06 and 11s, and the angulation of these teeth did not decrease with age in most arcades.

**Keywords: horse, anatomy, diastema, drift, angulation**



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## INTRODUCTION

Mammalian teeth within a complete dental arch normally drift in a mesial direction (toward the midline, i.e., between the first incisor teeth) with age. This normal, posteruptive dental movement is to compensate for normal interproximal dental wear at contact areas of adjacent teeth and so prevent abnormally wide interproximal spaces (diastemata) from developing. However, equine teeth do not form a continuous arch. Drift in the anteroposterior plane only, occurs in their straight row of six cheek teeth (i.e., second through fourth premolars and the three molar teeth) and equine mesial cheek teeth drift has been described as rostral drift (1–3).

Mesial drift is additionally needed by equine teeth because their long (clinical and reserve) crowns taper in toward their apices, thus making the clinical crowns in older horses progressively smaller in a mesio-distal direction following normal eruption and occlusal wear. This feature makes equine teeth more prone to developing diastemata with age (termed *senile diastemata*) (2).

The mechanisms of posteruption dental movement are complex and incompletely understood in all mammals. They include direct (approximal) pressure from adjacent teeth, vertical masticatory forces on teeth that are inclined (angulated, tipped) that causes anterior (mesial, rostral) or posterior (distal, caudal) teeth movement of the angulated and adjacent teeth, depending on their inclination. Pressure from the cheeks and tongue and contraction of transeptal fibers also play a part in dental movement in brachydont species (4–8).

In horses, the prolonged eruption of the mesially (rostrally) inclined clinical crowns [with distally (caudally) angulated reserve crowns] of the caudal cheek teeth, especially the Triadan 11 (third molar), directly forces the cheek teeth row in an anterior direction causing a mesial drift (2). In addition, mesial directed forces caused by occlusal pressures on these inclined teeth, also contributes to the mesial drift. A computed tomographic (CT) study showed equine third maxillary molars (Triadan 11) clinical crowns to have a mean mesial drift of 24.8 mm between horses under 6 and over 16 years of age (3).

As noted, equine teeth do not form a complete arch due to the presence of an (edentulous) interdental space (previously termed a *physiological diastema*) between their incisor and premolar teeth, and a necessary adaption is that the clinical crowns of the second premolar teeth (Triadan 06s) are inclined distally (caudally). These inclined 06s directly exert a caudally (distally) directed (approximal) pressure on the adjacent Triadan 07s and, thus, indirectly on the other cheek teeth. Additionally, as described earlier, masticatory pressures also exert a caudally directed force on these distally inclined teeth. A combination of the distally directed forces of the rostral cheek teeth in combination with mesial drift of the caudal cheek teeth normally keeps the six equine cheek teeth tightly compressed together occlusally.

Both mesial and distal equine cheek teeth drift have been demonstrated experimentally following extraction of maxillary 08s that showed marked narrowing of the extraction space (at a rate of 39–41% of the extraction site mesio-distal length per year) along with inclination of the clinical crowns of the remaining teeth into the extraction space from *both* directions (9, 10). Similarly, Townsend et al. show mesial and distal dental drift into the extraction sites of 50 clinical equine cases following cheek teeth exodontia with a mean closure of extraction sites of 16% (range 4–50%) per year along with inclination of all remaining teeth toward the extraction sites (11).

Studies in rats, which also have an interdental space between their incisor and molar teeth (rats have no premolars) show that dental drift into the empty alveolus following extraction of a molar is largely in a mesial direction (5, 6).

Cheek teeth diastemata with resultant periodontal disease is a very common equine dental disorder. A UK general practice study showing a prevalence of 50% in the general equine population (12). This disorder was also regarded as the most common, painful equine dental disorder in equine referral clinic studies (13, 14). The etiopathogenesis of this disorder is incompletely understood, but the presence of effective dental drift (in both directions) should bring and dynamically maintain the occlusal aspects of cheek teeth in tight occlusal contact and, thus, prevent or treat this disorder.

Interproximal dental wear due to individual movement of adjacent teeth and tapering of the cheek teeth crowns should cause equine cheek teeth rows to become shorter with age, but this feature does not appear to have been documented in horses.

No study has attempted to quantified distal (caudal) drift of equine maxillary or mandibular cheek teeth or mesial drift of equine mandibular cheek teeth using CT. This drift is largely governed by the angulation of teeth at the peripheries of the cheek teeth row. The curvature and position of the equine cheek teeth in horses of different ages was radiographically evaluated by Huthmann et al. (15). The maxillary cheek teeth curvature changed minimally with increasing age, but the mesio-occlusal angle of the maxillary cheek teeth did increase with age. There were less significant changes in the mandibular cheek teeth arcades (15).

A better understanding of equine cheek teeth drift may help explain why cheek teeth diastemata develops in some horses and may also indicate how this disorder may be prevented or treated.

The aim of this study was to quantify cheek teeth angulation in the mesio-distal plane, quantify mesial and distal mandibular and maxillary cheek teeth drift, and compare cheek teeth row length in horses of different ages using CT.

## MATERIALS AND METHODS

This study was approved by the Ethical Committee of the University of Edinburgh Veterinary School (52.21). Case details and CT images from clinical equine cases that had undergone standing CT head examination between January 1, 2011, and December 31, 2020, at R(D)SVS were collated.

### CT Examination

All CT studies were undertaken using standardized protocols optimized for the equine head. During the study period, two different CT scanners were used: from 2011 to 2016 a four-row MDCT unit (Somatom® Volume Zoom, Siemens, Germany)

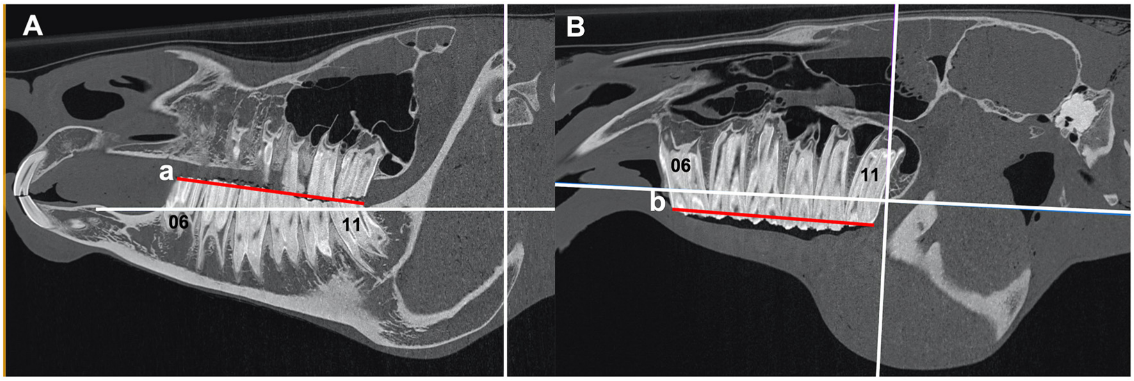


**FIGURE 1 | (A,B)** Sagittal CT images of an equine head showing the length (red lines) of the mandibular (a) and maxillary (b) arcades measured at the occlusal surface from the mesial aspect of 06 to the distal aspect of 11. The red line "a" and "b" shows the length of the mandibular and maxillary arcade, respectively.

with 3 mm slice thickness, 120 kVp, 100 mA, matrix 512 × 512, pitch 1 was used. The later cases were scanned with a 64-row MDCT scanner (Somatom® Definition AS Siemens, Erlangen, Germany) with slice thickness 0.6 mm, 120 kVp, 150 mA, matrix 512 × 512, pitch of 1.0.

## Case Selection

CT Images [bone window (H70)] were reviewed by a diagnostic imaging resident and diplomate using a computer workstation (Apple Mac Pro, Apple, USA) with a calibrated LCD flat screen monitor, using a dedicated DICOM viewer software (Horos, Purview, Annapolis MD, USA, version 3.3.6).

Cases with CT evidence of any of the following: motion artifact during image acquisition, missing or supernumerary teeth, cheek teeth diastemata, displaced or fractured cheek teeth, or craniofacial abnormalities (e.g., brachygnathism or prognathism) were excluded from the study.

## CT Measurements

Three sets of measurements were acquired for this study. Sagittal plane CT reconstructions were used to make measurements using the calibrated measuring tools in DICOM viewer software.

1) *Head size*
   The distance between the caudal aspect of the orbit and the caudal aspect of the naso-incisive notch was measured in all cases and was used as an estimate of head size.
2) *The length of the cheek teeth rows*
   Measured from the mesial aspect of the Triadan 06 occlusal surface to the distal aspect of the Triadan 11 occlusal surface (**Figures 1A,B**).
3) *The rostro-caudal (antero-posterior) position and angulation of the mandibular and maxillary Triadan 06 and 11 teeth*
   Measured in relation to reference lines drawn on CT images.

## 3a) Mandibular Teeth

For each mandibular cheek teeth row, two reference lines were drawn:

a. A line intersecting the dorsal aspect of the mandibular bone immediately mesial to the mandibular second premolar (Triadan 06) tooth and the dorsal aspect of the mandibular bone immediately distal to the mandibular third molar (Triadan 11) tooth (Line "a") (**Figures 2A,B**, **3A,B**).
b. A line at the level of the rostral aspect of the mandibular condyle that lay perpendicular to line "a" (Line "b") (**Figures 2A,B**, **3A,B**).

### Antero-Posterior (Rostro-Caudal) Position of Teeth

Distances from reference line "b" to the distal aspects of the mandibular Triadan 06 and 11 teeth were measured at the most occlusal and apical aspects of the Triadan 06 and 11 teeth (red and green lines "c" and "d") (Man 06 DiO, Man 06 DiA, Man 11 DiO, Man 11 DiA) (**Figures 2A,B**).

### Angles of Triadan 06 and 11 Teeth

Lines of best fit were drawn along the central long axis extending from the occlusal surface to the reserve crowns of the mandibular Triadan 06 and 11 teeth, and the angle of these lines in relation to line "b" were calculated (Man 06 Ang and Man 11 Ang) (**Figures 3A,B**).

## 3b) Maxillary Teeth

For each maxillary cheek teeth row, two reference lines were drawn as previously described (3).

a. A line intersecting the ventral aspect of the maxillary bone immediately mesial to the maxillary Triadan 06 tooth to the dorsal aspect of the mandibular bone immediately distal to the mandibular Triadan 11 tooth (**Figures 4A,B**, **5A,B**).
b. A line perpendicular to line "c" at the level of the rostral aspect of the orbit (**Figures 4A,B**, **5A,B**).

### Antero-Posterior (Rostro-Caudal) Position of Teeth

Distances from reference line "d" to the distal aspects of the maxillary Triadan 06 and 11 teeth were measured at the most occlusal and apical aspects of these teeth (Max 06 DiO, Max 06 DiA, Max 11 DiO, Max 11 DiA). Measurements rostral to

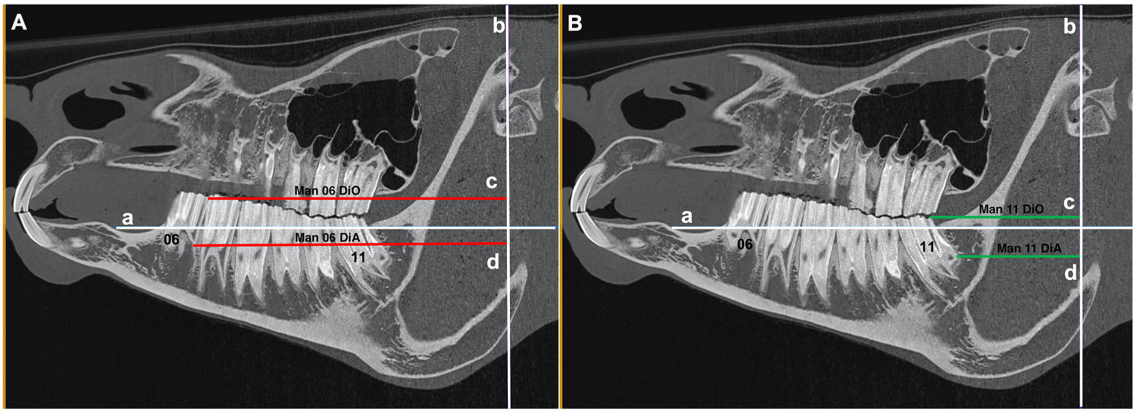


**FIGURE 2 | (A)** Sagittal CT image of an equine head showing line "a" that intersects the dorsal aspect of the mandibular bone immediately mesial to the mandibular second premolar (Triadan 06) tooth and the dorsal aspect of the mandibular bone immediately distal to the mandibular third molar (Triadan 11) tooth and line "b" at the level of the rostral aspect of the mandibular condyle that lies perpendicular to line "a." The red lines "c" (Man 06 DiO) and "d" (Man 06 DiA) run from the line "b" to the distal aspect of the occlusal surface of Triadan 06 and to the distal aspect of the apex of Triadan 06, respectively. **(B)** Sagittal CT image of an equine head showing line "a" that intersects the dorsal aspect of the mandibular bone immediately mesial to the mandibular second premolar (Triadan 06) tooth and the dorsal aspect of the mandibular bone immediately distal to the mandibular third molar (Triadan 11) tooth and line "b" at the level of the rostral aspect of the mandibular condyle that lies perpendicular to line "a." The green lines "c" (Man 11 DiO) and "d" (Man 11 DiA) run from the line "b" to the distal aspect of the occlusal surface of Triadan 11 and to the distal aspect of the apex of Triadan 11, respectively.

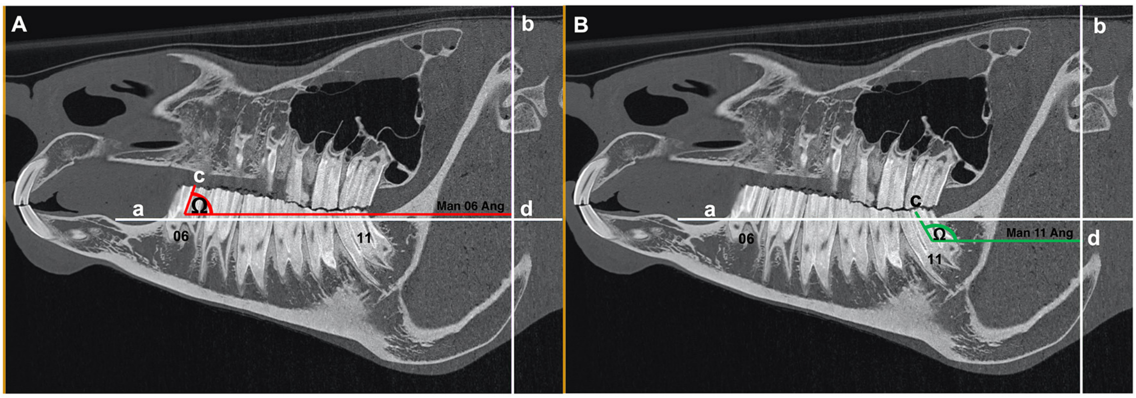


**FIGURE 3 | (A)** Sagittal CT image of an equine head showing line "a" that intersects the dorsal aspect of the mandibular bone immediately mesial to the mandibular second premolar (Triadan 06) tooth and the dorsal aspect of the mandibular bone immediately distal to the mandibular third molar (Triadan 11) tooth and line "b" at the level of the rostral aspect of the mandibular condyle that lies perpendicular to line "a." The red line "c" drawn through the central long axis of mandibular Triadan 06 intersects line "d" that lies parallel to line "a" and perpendicular to line "b." The angle (Ω) created with the intersection of line "c" and line "d" was measured (Man 06 Ang). **(B)** Sagittal CT image of an equine head showing line "a" that intersects the dorsal aspect of the mandibular bone immediately mesial to the mandibular second premolar (Triadan 06) tooth and the dorsal aspect of the mandibular bone immediately distal to the mandibular third molar (Triadan 11) tooth and line "b" at the level of the rostral aspect of the mandibular condyle that lies perpendicular to line "a." The green line "c" drawn through the central long axis of mandibular Triadan 11 intersects line "d" that lies parallel to line "a" and perpendicular to line "b." The angle (Ω) created with the intersection of line "c" and line "d" was measured (Man 11 Ang).

line "d" were positive and those caudal to it were negative (**Figures 4A,B**).

### Angles of Teeth

Lines of best fit were drawn along the central long axis extending from the occlusal surface to the reserve crowns of the maxillary Triadan 06 and 11 teeth and the angle of these lines in relation to line "d" were calculated (Max 06 Ang and Max 11 Ang) (**Figures 5A,B**).

## Statistical Analyses

The mean of left- and right-sided measures were used for analyses. Linear and dental angle measures and horse ages were assessed for normality by graphical assessment and using Shapiro–Wilks tests, the results of which were used to guide appropriate statistical test choice (i.e., parametric or non-parametric).

To allow comparison of tooth positions and cheek teeth row lengths between ages while accounting for differences in head

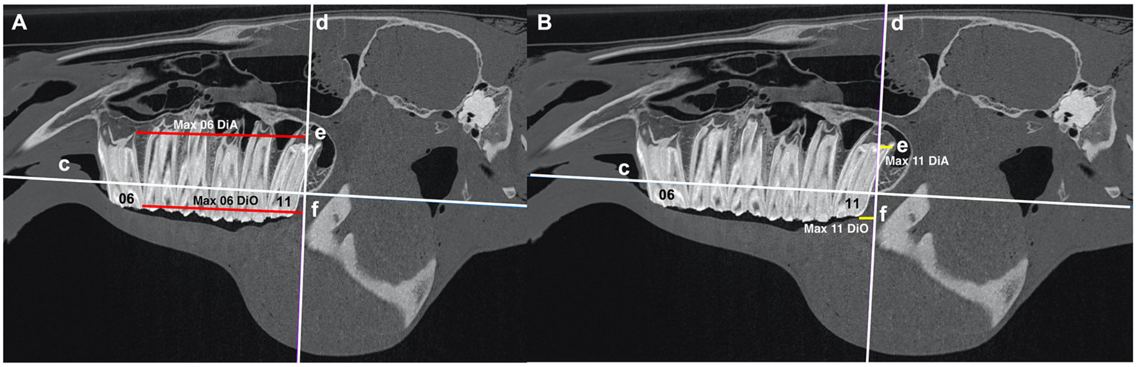


**FIGURE 4 | (A)** Sagittal CT image of an equine head showing line "c" that intersects the dorsal aspect of the maxillary bone immediately mesial to the maxillary second premolar (Triadan 06) tooth and the dorsal aspect of the maxillary bone immediately distal to the maxillary third molar (Triadan 11) tooth and line "d" at the level of the rostral orbit that lies perpendicular to line "c." The red lines "e" (Max 06 DiA) and "f" (Max 06 DiO) run from line "d" to the distal aspect of the occlusal surface of Triadan 06 and to the distal aspect of the apex of Triadan 06, respectively. **(B)** Sagittal CT image of an equine head showing line "c" that intersects the dorsal aspect of the maxillary bone immediately mesial to the maxillary second premolar (Tridan 06) tooth and the dorsal aspect of the maxillary bone immediately distal to the maxillary third molar (Triadan 11) tooth and line "d" at the level of the rostral orbital rim that lies perpendicular to line "c." The yellow lines "e" (Max 11 DiA) and "f" (Max 11 DiO) run from the line "d" to the distal aspect of the occlusal surface of Triadan 11 and to the distal aspect of the apex of Triadan 11, respectively.

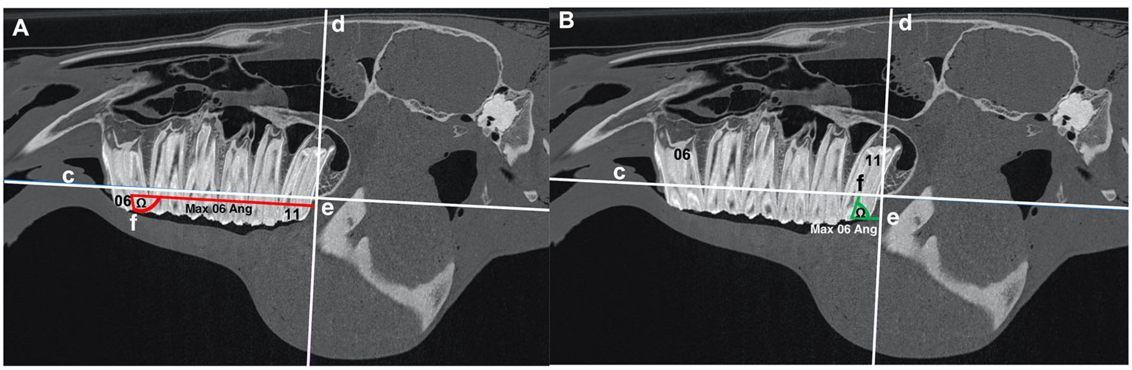


**FIGURE 5 | (A)** Sagittal CT image of an equine head showing line "c" that intersects the dorsal aspect of the maxillary bone immediately mesial to the maxillary second premolar (Triadan 06) tooth and the dorsal aspect of the maxillary bone immediately distal to the maxillary third molar (Triadan 11) tooth. Line "d" is at the level of the rostral orbit and lies perpendicular to line "c." The red line "f" drawn through the central long axis of maxillary Triadan 06 intersects line "e" that lies parallel to line "c" and perpendicular to line "d." The angle (Ω) created by the intersection of line "f" and line "e" was measured (Max 06 Ang). **(B)** Sagittal CT image of an equine head showing line "c" that intersects the dorsal aspect of the maxillary bone immediately mesial to the maxillary second premolar (Tridan 06) tooth and the dorsal aspect of the maxillary bone immediately distal to the maxillary third molar (Triadan 11) tooth. Line "d" at the level of the rostral orbit lies perpendicular to line "c." The green line "f" drawn through the central long axis of the maxillary Triadan 11 intersects line "e" that lies parallel to line "c" and perpendicular to line "d." The angle (Ω) created by the intersection of line "f" and line "e" was measured (Max 11 Ang).

sizes, adjusted rostro-caudal position measures, and adjusted row lengths were calculated ("adjusted measures") by scaling to the mean measured head size of the samples.

For example, in a case with head size 10% smaller than the mean size, tooth position measures were increased by 10%.

Dental angle measures were not adjusted for head size.

The associations between horse age and "adjusted measures" as well as dental angle were compared using Pearson correlation and simple linear regression. Statistical analyses and production of graphs were performed in RStudio™. Significance was set at $P < 0.05$.

To allow comparisons with a previous study Liuti et al. (3) mean values were calculated for measures between age groups: <6, 6–15, and >15 years.

## RESULTS

A total of 67 cases were included in this study based on the above inclusion criteria with 291 cases excluded having not met the inclusion criteria. There were 23 cases from 2011 to 2016 and 44 cases from 2017 to 2020 of mean age 10.8 years (SD: 4.1; range: 3–21 years) and included 24 females and 43 males. Breed distribution is shown in **Table 1**. The main reasons for these CT head examinations included suspected cheek teeth apical infection, head shaking, ataxia, and head trauma.

Mean measures (absolute and adjusted) of distance and mean angles for each site as well as cheek teeth row lengths are shown in **Table 2**. Mean values for measures subdivided by different age groups are shown in **Table 3**.

The Triadan 06 teeth clinical crowns were angled (inclined) distally, and the Triadan 11 teeth clinical crowns were inclined mesially with, on average, slightly more angulation in the mandibular teeth, which could be observed in the difference between the occlusal and apical rostro-caudal measures and by the angle measurements (**Table 2**).

## Associations Between Measures and Age

Associations between age and adjusted measures as well as dental angles are shown in **Table 2** and **Figures 6–9**. These associations were not simply linear with much variation across the population, reflected in the correlation coefficients, which range from low to moderate correlation.

**TABLE 1** | Breed distribution in the study population.

| Breed | Number |
|---|---|
| Thoroughbred and crosses | 26 |
| Sports horses | 14 |
| Warmblood | 8 |
| Irish Draft and crosses | 3 |
| Crossbreed | 3 |
| Welsh Cob | 3 |
| Welsh Pony | 3 |
| Connemara | 2 |
| Arabian | 1 |
| Clydesdale cross | 1 |
| Highland pony | 1 |
| Pony | 1 |
| Shetland Pony | 1 |

## Dental Drift

Measures of the apical and occlusal aspects of maxillary and mandibular 06 and 11s (**Table 2** and **Figures 6**, **7**) show the presence of age-related changes, including a moderate correlation in maxillary 06 disto-occlusal measure (0.32), maxillary 11 disto-apical and disto-occlusal measures (0.5 and 0.41, respectively), mandibular 11 disto-occlusal and disto-apical measures 0.37 and 0.46, respectively), mandibular 06 angle (0.37) and low correlation in maxillary 06 disto-apical and mandibular 06 disto-occlusal measures (0.22 and 0.26, respectively), mandibular 06 disto-apical measure (0.14), the maxillary and mandibular 11 angles (0.18 and −0.18, respectively), and the maxillary 06 angle (−0.08) and the maxillary and mandibular cheek teeth arcade (row) lengths (−0.14 and −0.21, respectively).

There was significant positive association between age and the adjusted disto-apical and disto-occlusal measures for the maxillary 11 and mandibular 11 teeth as well as with the adjusted disto-occlusal measure for the maxillary and mandibular 06 teeth and the mandibular 06 angles, indicating that both the 06 and 11 cheek teeth move mesially with age.

## Dental Angulation

The mandibular Triadan 06s (mean 17.8° off vertical) and 11s (mean 26.2°) had almost double the angulation of their maxillary 06 (mean 9.2°) and 11 (mean 13.3°) counterparts (**Table 2** and **Figure 8**). Additionally, in both maxillary and mandibular teeth, the 06 angulation was lower than the Triadan 11 angulation (69

**TABLE 2** | Mean measures (cm) and angles (degrees) and adjusted measures for each site from 67 horses.

| Site | Mean measure cm (SD) | Mean adjusted measure cm (SD) | Association with age | |
|---|---|---|---|---|
| | | | Pearson correlation | Lin reg *p*-value |
| **Maxillary** | | | | |
| Max 06 DiA | 15.6 (1.6) | 15.4 (1.0) | 0.22 | 0.080 |
| Max 06 DiO | 14.5 (1.5) | 14.4 (1.1) | 0.32 | **0.009** |
| Max 06 Ang | 80.8 (5.1) | | −0.08 | 0.522 |
| Max 11 DiA | −0.3 (1.1) | −0.4 (1.1) | 0.50 | **<0.001** |
| Max 11 DiO | 0.5 (0.9) | 0.5 (0.9) | 0.41 | **<0.001** |
| Max 11 Ang | 103.3 (4.7) | | 0.18 | 0.138 |
| Arcade Length | 19.0 (1.6) | 18.8 (1.4) | −0.14 | 0.345 |
| **Mandible** | | | | |
| Man 06 DiO | 27.9 (2.1) | 27.7 (2.0) | 0.26 | **0.034** |
| Man 06 DiA | 29.4 (2.1) | 29.3 (2.0) | 0.14 | 0.258 |
| Man 06 Ang | 72.2 (4.4) | | 0.37 | **0.002** |
| Man 11 DiO | 13.4 (1.4) | 13.3 (1.4) | 0.37 | **0.001** |
| Man 11 DiA | 11.5 (1.5) | 11.4 (1.5) | 0.46 | **<0.001** |
| Man 11 Ang | 116.2 (5.1) | | −0.18 | 0.136 |
| Arcade length | 19.2 (1.7) | 19.0 (1.6) | −0.21 | 0.095 |

*Results of comparisons of angles and adjusted measures with age shown as Pearson correlation coefficients, and P-values generated from simple linear regression (Lin reg). Significant associations shown in bold. Sites: Max, maxillary; Man, mandibular; DiA, Disto-Apical; DiO, Disto-Occlusal; Ang, Angle; numbers, Triadan tooth position.*

**TABLE 3 |** Mean adjusted measures (cm) and angles (degrees) for each site from 67 horses subdivided by age groups.

| Site | Mean adjusted* measure cm (SD) | Mean adjusted* measure (SD) | | |
|---|---|---|---|---|
| | | Age group 1 (*n* = 5) <6 years | Age group 2 (*n* = 51) 6–15 years | Age group 3 (*n* = 11) >16 years |
| **Maxillary** | | | | |
| Max 06 DiA | 15.4 (1.0) | 14.6 (0.4) | 15.4 (1.1) | 15.8 (0.8) |
| Max 06 DiO | 14.4 (1.1) | 13.5 (0.6) | 14.4 (1.1) | 15.0 (0.8) |
| Max 06 Ang | 80.8 (5.1) | 81.1 (5.3) | 81.0 (5.1) | 79.8 (5.3) |
| Max 11 DiA | −0.4 (1.1) | −1.5 (1.1) | −0.6 (0.8) | 1.1 (0.9) |
| Max 11 DiO | 0.5 (0.9) | −0.3 (0.8) | 0.4 (0.8) | 1.5 (0.8) |
| Max 11 Ang | 103.3 (4.7) | 100.7 (4.7) | 103.2 (4.3) | 105.4 (6.1) |
| Arcade Length | 18.8 (1.4) | 18.6 (1.3) | 19.0 (1.5) | 17.9 (1.1) |
| **Mandible** | | | | |
| Man 06 DiO | 27.7 (2.0) | 27.0 (0.8) | 27.6 (2.0) | 28.3 (2.0) |
| Man 06 DiA | 29.3 (2.0) | 29.1 (0.8) | 29.3 (2.1) | 29.5 (1.9) |
| Man 06 Ang | 72.2 (4.4) | 69.1 (2.8) | 71.9 (4.2) | 75.3 (4.6) |
| Man 11 DiO | 13.3 (1.4) | 12.7 (1.2) | 13.2 (1.4) | 14.2 (1.3) |
| Man 11 DiA | 11.4 (1.5) | 10.0 (1.0) | 11.3 (1.3) | 12.6 (1.9) |
| Man 11 Ang | 116.2 (5.1) | 115.7 (4.9) | 116.8 (5.2) | 113.9 (4.9) |
| Arcade length | 19.0 (1.6) | 19.6 (1.2) | 19.1 (1.6) | 18.2 (1.2) |

*Sites: Max, maxillary; Man, mandibular; DiA, Disto -Apical; DiO, Disto -Occlusal; Ang, Angle; numbers, Triadan tooth position. *Angles not adjusted – shaded gray.*

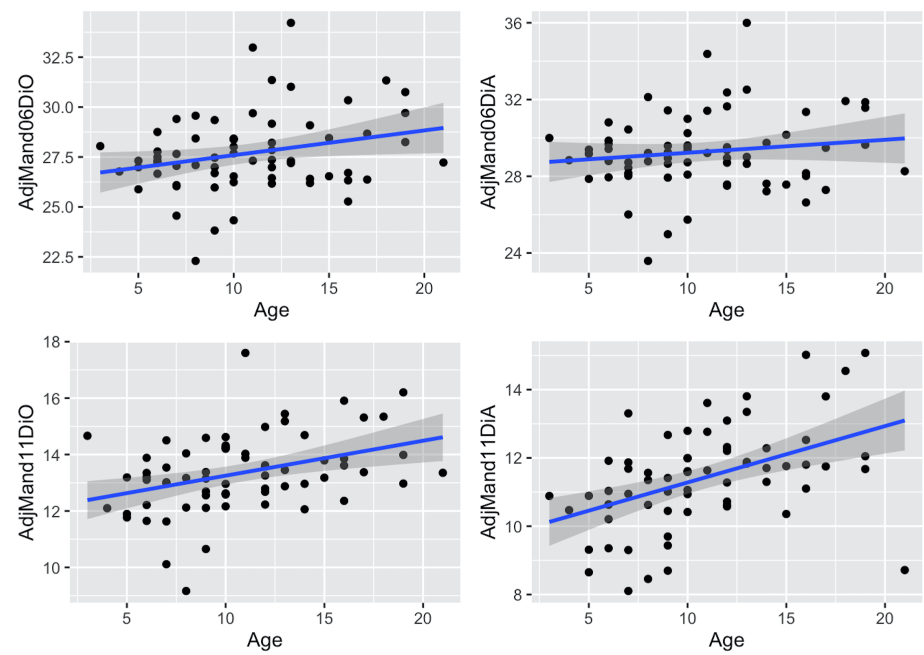


**FIGURE 6 |** Scatterplots with linear regression lines (blue) and confidence intervals (gray shading) plotted, showing associations between age (years) and adjusted rostro-caudal position measures (cm) (mean of left and right sides) for the maxillary cheek teeth in 67 horses. AdjMax06DiA, adjusted maxillary 06 disto-apical measurement; AdjMax06DiO, adjusted maxillary 06 disto-occlusal measurement; AdjMax11DiA, adjusted maxillary 11 disto-apical measurement; AdjMax11DiO, adjusted maxillary 11 disto-occlusal measurement. Negative measurements occur when the Triadan 11s are caudal to the orbit.

and 68%, respectively, for maxillary 11s and mandibular 11s). Age-related decreases in angulation were found in mandibular and maxillary 06 and 11s but were significant only in the mandibular 06 teeth.

## Arcade Lengths

Although both the maxillary and mandibular cheek teeth arcade lengths decreased with age (**Table 2** and **Figure 9**), this decrease was not statistically significant in either cheek teeth row.

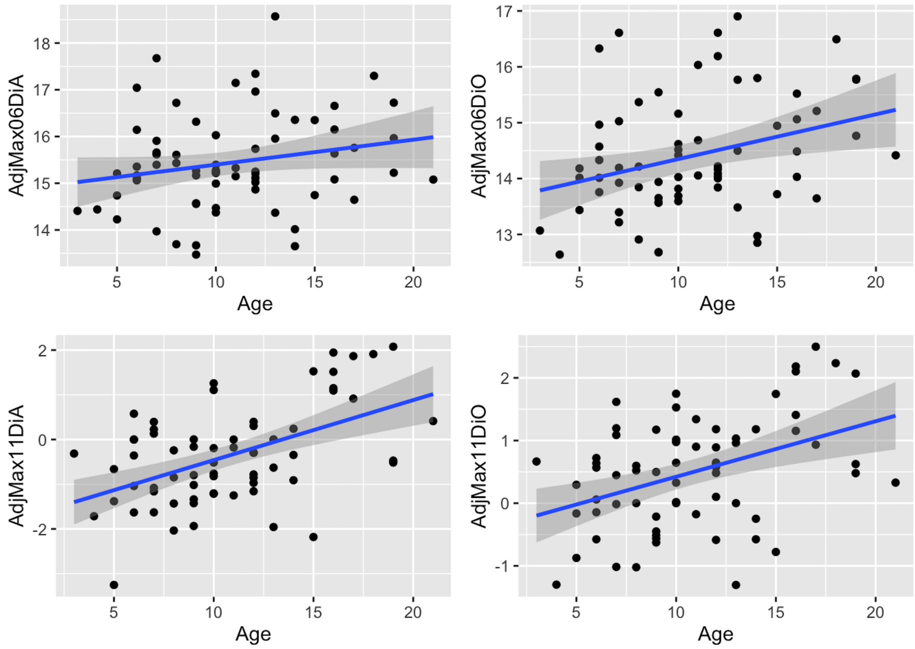


**FIGURE 7 |** Scatterplots with linear regression lines (blue) and confidence intervals (dark gray shading) plotted, showing associations between age (years) and adjusted rostro-caudal position measures (mean of left and right) for the mandibular teeth in 67 horses. AdjMand06DiO, adjusted mandibular 06 disto-occlusal measurement; AdjMand06DiA, adjusted mandibular 06 disto-apical measurement; AdjMand11DiO, adjusted mandibular 11 disto-occlusal measurement; AdjMand11DiA, adjusted mandibular 11 disto-apical measurement.

## DISCUSSION

This study confirms the presence of age-related mesial drift of the caudal (Triadan 11s) equine maxillary cheek teeth previously quantified by Liuti et al. (3) with a mesial drift of 9 mm found between the <6 y.o. group and the 6–15 y.o. group and of 15 mm between the former and the >16 y.o. group in this study. Unexpectedly, the apical aspects of these teeth drifted slightly less (12 mm between the <6 and >16 y.o groups) as it was expected that their caudally facing apices would shorten as well as drift and, thus, overall have a higher measure of mesial drift than the occlusal aspects as was found by Liuti et al., who recorded drift of 24.8 mm in the occlusal surface and 28.3 mm in the maxillary Triadan 11s of similar age groups of horses.

Age-related mesial drift has not been reported in maxillary Triadan 06s. This study shows a mean mesial drift of 15 and 12 mm, respectively, in the occlusal and apical aspects of maxillary 06s between the <6 and >16 y.o groups. The apical aspects of these mesially facing apices drifted slightly less as expected as they became short as well as drifting mesially.

Equine mandibular cheek teeth dental drift has also not previously been documented. Similarly to the maxillary cheek teeth, there was an increased level of mesial drift of the distally facing apices (26 mm) as compared with their occlusal aspects (18 mm) of the mandibular Triadan 11 teeth (**Table 3**) because of a mesially directed eruption of these apices as well as mesial dental drift. For similar reasons, there was *less* drift of the apices of the mandibular 06s (4 mm) compared with their occlusal aspects (13 mm) between the youngest and oldest age groups.

The age-related movement of the Triadan 06s is more complex to understand because of the competing forces of mesial drift induced by the angulation of the Triadan 11 (and possibly by the variably angulated Triadan 10 teeth) and the distally directed forces resulting from the (angulated) Triadan 06 teeth themselves.

Following extraction of teeth within the equine cheek teeth row, the anterior teeth drift distally and also incline into the extraction site (9–11). However, the net result of normal age-related, posteruption movements found in this study was a mesial drift of the Triadan 06s (maxillary 15 mm, mandibular 13 mm) of similar magnitude to the Triadan 11s (maxillary 18 mm, mandibular 15 mm) (**Table 3**).

These finding indicate that the mesially directed forces are greater than the distally directed forces. This may be explained by the much greater angulation of both the mandibular and maxillary 11s (mean of all of horses of 26.2° and 13.3°, respectively) compared with the lower and upper 06s (17.8° and 9.2°, respectively) and also because the occlusal pressures are highest more caudally in the oral cavity.

It was hypothesized that there would be an age-related decrease in cheek teeth angulation with age, but there was significant age-related change in angulation only in the mandibular 06 teeth (decreased from 20.9° in the youngest to 14.7° in the oldest group) and a non-significant decrease in the mandibular 11s (from 25.7° to 23.9°). However, in the maxillary

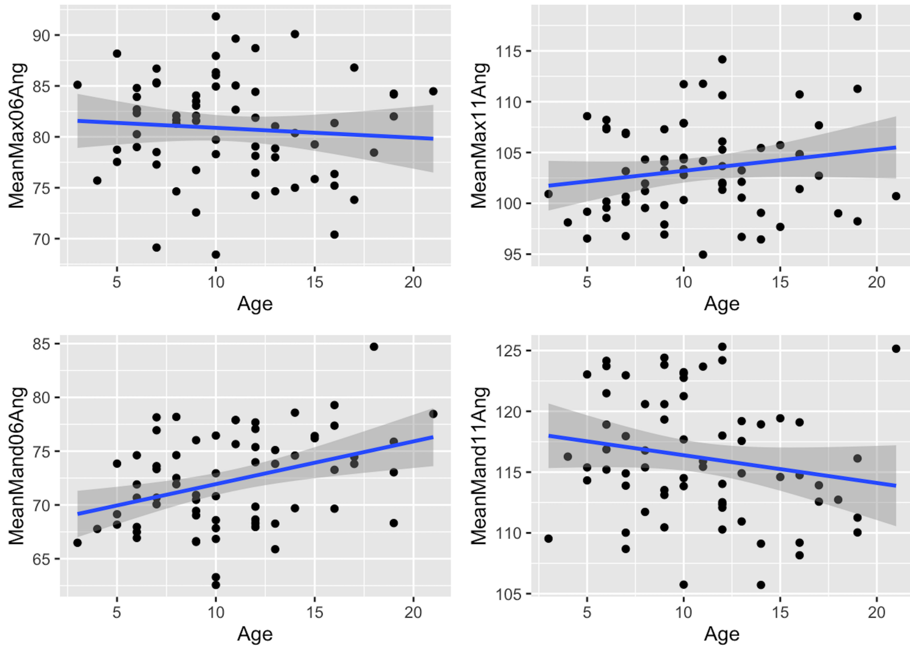


**FIGURE 8 |** Scatterplots with linear regression lines (blue) and confidence intervals (dark gray shading) plotted, showing associations between age (years) and crown angles (mean of left and right) of the Triadan 06 and 11 teeth in 67 horses. MeanMax06Ang, maxillary 06 angle; MeanMax11Ang, maxillary 11 angle; MeanMand06Ang, mandibular 06 angle; MeanMand11Ang, mandibular 11 angle.

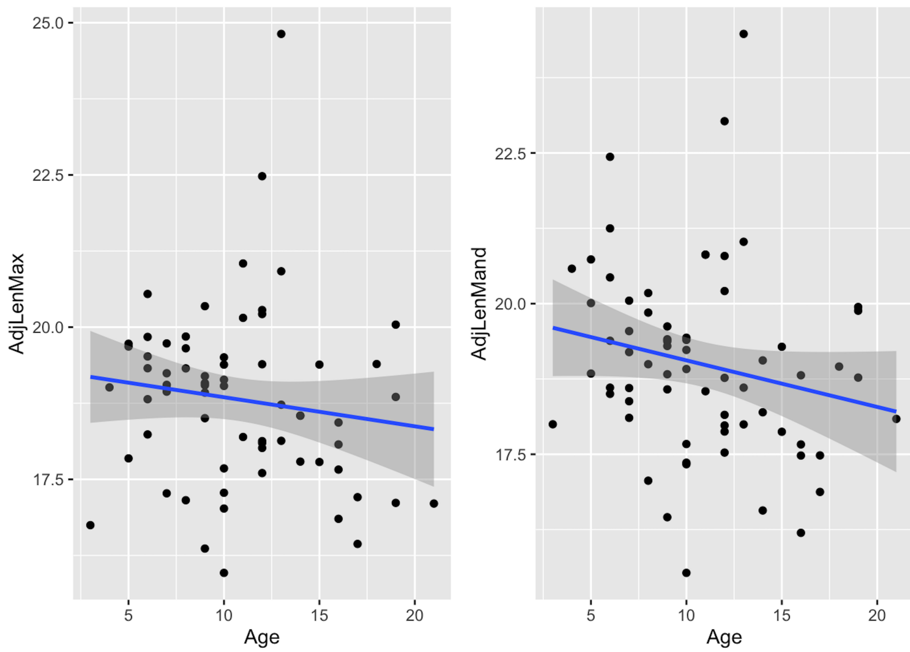


**FIGURE 9 |** Scatterplots with linear regression lines (blue) and confidence intervals (dark gray shading) plotted, showing associations between age (years) and adjusted cheek teeth arcade lengths (cm) in 67 horses. AdjLenMax, adjusted mean maxillary cheek teeth arcade length; AdjLenMand, adjusted mean mandibular cheek teeth arcade length.

cheek teeth, the angles actually increased (from 8.9° to 11.2° in the 06s and from 10.7° to 15.4° in the 11s) between the youngest and oldest groups. The maintenance of adequate cheek teeth angulation appears to be pivotal in maintaining tight interdental contact in teeth, and so it should not be surprising that adequate angulation was maintained.

Limitations in these cheek teeth angulation measurements include that these angles were taken as the line of best fit of the clinical and more occlusal aspect of the reserve crown rather than from the more angulated apical aspects of these teeth with curved roots, a feature of older mandibular cheek teeth. With more advanced age-related wear, some 06 and 11 angulations are fully lost when the reserve crowns become very short with wear.

Examination of the association between the cheek teeth row lengths and horse age showed a non-significant trend toward reduction with age from a mean of 18.6 mm long on the youngest to 17.9 mm in the oldest group in the maxillary cheek teeth and from 19.6 to 18.2 mm long in the mandibular arcade. Examination of the clinical crowns of equine cheek teeth shows the obvious presence of interdental wear, including the complete loss of peripheral cementum at these sites. This interproximal wear in conjunction with the tapering crowns of equine teeth results in shorter cheek teeth rows in older horses. If larger numbers of horses were examined, these measurements may have become statistically significant. Limitations on these measurements include the variable curvature of the equine cheek teeth occlusal surface, including, more caudally, the curve of Spee.

Another limitation is the small number of horses included in this study. Despite having collated 358 studies of horses that underwent standing head CT, 291 were removed due to motion artifact during image acquisition, missing or supernumerary teeth, cheek teeth diastemata, displaced or fractured cheek teeth, or craniofacial abnormalities (e.g., brachygnathism or prognathism). It was considered important to use these strict exclusion criteria to remove the potential impact of these factors on the measurements.

The development of mobile platforms that allow CT imaging in standing sedated horses is a major improvement with reduced costs and morbidity/mortality risks when compared with general anesthesia as previously noted (16, 17). However, motion artifact is commonly seen during image acquisition, and it is considered the main cause of poor image quality (18).

From a clinical perspective, this study shows that, in general, horses maintain the occlusal angulations of their cheek teeth well into their adulthood. This angulation appears to be the prime factor in keeping the cheek teeth occlusal surfaces in close contact and preventing diastemata from developing. Overall, the mesial drift caused by the caudal cheek teeth, especially the 11s, is stronger than the distal drift induced by the 06s, resulting in an overall mesial drift while keeping all occlusal surfaces together. For these angulated teeth to be effective in causing both mesial and distal dental drift, adequate occlusal forces must be applied to them, and thus, relieving dental pain by treating periodontal disease would appear useful. Likewise, all teeth should be free to drift, and thus, removal of any occlusal overgrowths that may restrict such drift is also essential.

## CONCLUSIONS

In the population of horses used for this study, age-related mesial drift occurred in both Triadan 06 and 11s, and the angulation of these teeth also decreased with age. A study with a larger number of cases with more age variability and/or following horses over their lives would be useful to better understand the development of certain conditions such as diastemata.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## ETHICS STATEMENT

This study was approved by the Ethical Committee of The University of Edinburgh Veterinary School (52.21). Written informed consent was obtained from the owners for the participation of their animals in this study.

## AUTHOR CONTRIBUTIONS

TL, PD, and RR contributed to conception, design of the study, and wrote sections of the manuscript. TL and CD organized the database. RR performed the statistical analysis. PD wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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