ANTHROPOLOGY

Correction for “Origins of equine dentistry,” by William Timothy Treal Taylor, Jamsranjav Bayarsaikhan, Tumurbaatar Tuvshinjargal, Scott Bender, Monica Tromp, Julia Clark, K. Bryce Lowry, Jean-Luc Houle, Dimitri Staszewski, Jocelyn Whitworth, William Fitzhugh, and Nicole Boivin, which was first published July 2, 2018; 10.1073/pnas.1721189115 (Proc Natl Acad Sci USA 115:E6707–E6715).

The authors note that the following statement should be added to the Acknowledgments: “We thank Dr. Tserendorj Odbaatar and Dr. Bryan Miller for conducting original excavations at the archaeological sites of Elst-Ar, Airagiin Gozgor, and Takhilt, which represent a major and important contribution to this research.”

The authors also note that a reference was omitted from the article. The complete reference appears below. A citation to this reference should be included on page E6711, right column, first full paragraph, line 5, following “Mongolia.”


Published under the PNAS license.

Published online September 24, 2018.

www.pnas.org/cgi/doi/10.1073/pnas.1815049115
Origins of equine dentistry

William Timothy Treal Taylor, Jamsranjav Bayarsaikhan, Tumurbaatar Tuvshinjargal, Scott Bender, Monica Tromp, Julia Clark, K. Bryce Lowry, Jean-Luc Houle, Dimitri Stasiewski, Jocelyn Whitworth, William Fitzhugh, and Nicole Boivin

*Department of Archaeology, Max Planck Institute for the Science of Human History, 07745 Jena, Germany; †National Museum of Mongolia, 21046 Ulaanbaatar, Mongolia; ‡Navajo Technical University, Crownpoint, NM 87313; †American Center for Mongolian Studies, 15160 Ulaanbaatar, Mongolia; §Department of Anthropology, University of Chicago, Chicago, IL 60637; †Western Kentucky University, Bowling Green, KY 42101; ‡Private address, Philadelphia, PA 19146; †Clearview Animal Hospital, Colorado Springs, CO 80911; and †Arctic Studies Center, Smithsonian Institution, Washington, DC 20560

Edited by Melinda A. Zeder, National Museum of Natural History, Santa Fe, NM, and approved May 22, 2018 (received for review January 23, 2018)

From the American West to the steppes of Eurasia, the domestic horse transformed human societies, providing rapid transport, communication, and military power, and serving as an important subsistence animal. Because of the importance of oral equipment for horse riding, dentistry is an essential component of modern horse care. In the open grasslands of northeastern Asia, horses remain the primary form of transport for many herders. Although free-range grazing on gritty forage mitigates many equine dental practices have great antiquity. Anthropogenic modifications to domesticated deciduous central incisors in young horses from the Late Bronze Age demonstrate their attempted removal, coinciding with the local innovation or adoption of horseback riding and the florescence of Mongolian pastoral society. Horse specimens from this period show no evidence of first premolar removal, which we first identify in specimens dating to ca. 750 BCE. The onset of premolar extraction parallels the archaeological appearance of jointed bronze and iron bits, suggesting that this technological shift promoted innovations in dentistry that improved horse health and horse control. These discoveries provide the earliest directly dated evidence for veterinary dentistry, and suggest that innovations in equine care by nomadic peoples ca. 1150 BCE enabled the use of horses for increasingly sophisticated mounted riding and warfare.

Significance

The domestication of horses and adoption of horse riding were critical processes that culminated in the emergence of mounted warriors and nomadic empires that shaped world history. The constraints of horse biology and riding equipment meant that equine veterinary care, particularly of teeth, was a core component of the success of the human–horse relationship. We report the earliest evidence of equine dentistry, from the Mongolian Steppes, at 1150 BCE. Key shifts in equine dentistry practice through time can be linked first to the emergence of horseback riding and later to the use of metal bits that enabled better control of horses. The maintenance of horse health through dentistry underwrote the key role of horses in cultures and economies around the world.

Author contributions: W.T.T.T. designed research; W.T.T.T., J.B.L., T.T., S.B., J.C., K.B.L., J.-L.H., D.S., J.W., W.F., and N.B. performed research; M.T. contributed new reagents/analytic tools; W.T.T.T. and M.T. analyzed data; and W.T.T.T. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. Published under the PNAS license.

1To whom correspondence should be addressed. Email: taylor@shh.mpg.de.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1721189115/-/DCSupplemental.

Published online July 2, 2018.

www.pnas.org/cgi/doi/10.1073/pnas.1721189115

PNAS | vol. 115 | no. 29 | E6707–E6715
number up to 200,000, but the supply of horses was controlled by
the same steppe “barbarians” who used them to raid and destroy
(14), and sold them to Chinese buyers at great expense (13).
Without the ability to sustainably breed them in large numbers,
the appropriate health care of these animals was paramount. As
early as the first millennium BCE, Chinese states thus provided
formal veterinary care for horses (15). One of the earliest equine
veterinary texts is credited to a Chinese author from the Spring
and Autumn Period, ca. 770–476 BCE, and over subsequent
centuries, veterinary care of horses played an increasingly formal-
ized role in Chinese government bureaucracy and state infra-
structure (15). Greek and Roman texts also indicate the
development of specialized horse care in the classical world by the
mid- to late first millennium BCE, and many of the most important
early veterinary texts focused heavily on the care of horses and other equids (16, 17).

Despite the apparent significance of equine veterinary care in
China and other ancient societies, the origins of equine dental
care are poorly understood. Dental health is of systemic im-
portance to the health of almost any animal (18), and some
scholars hypothesize that it must have been practiced by early
charioteers in western Asia and the Near East (11); however,
very little physical or textual evidence exists to support infer-
ces of equine dentistry during the Eneolithic or Bronze Age.
Some archaeologists hypothesize that a strange wear pattern
found on a horse from the site of Buhen, Egypt, dated to ca. 1675
BCE was produced by dental filing of the lower second premolar
(19), although the most likely explanation of this damage is “bit
wear,” damage caused directly to a tooth by a bit during use (20).
The first definitive record of horse dentistry also comes from
early Chinese veterinary texts dating to ca. 600 BCE, which describe
the method of aging a horse through changes in its dentition (21, 22).
During the Roman Empire, Aristotle and others made detailed
mention of equine periodontal disease in their writings (21). By the
Middle Ages, numerous Islamic texts refer directly to the practice of
filing of sharp points in the animal’s mouth (22, 23), clear evidence
that intentional modification of the teeth was practiced by this time.

Nonetheless, examples of major uncorrected occlusal issues in ar-
chaeological equids are known even from this period (18, 24),
indicating that equine dental care was far from ubiquitous. Because
of the ambiguity of both historical records and putative dental
modifications found on early archaeofaunal remains, it is difficult to
reliably assess when the first equine dental care arose, or its
relationship to broader developments in the domestication, spread,
and riding of horses across Eurasia.

**Contemporary Equine Dental Care**

Horse teeth are subject to continuous wear that is replaced by
tooth eruption throughout the animal’s life, which means that
minor issues with posture and occlusion can cause chronic dental
problems. Much of contemporary equine dental work in the
United States and other Western countries is focused on cor-
recting these occlusal issues, which can cause issues with feeding
and behavior. A second major goal of horse dentistry centers on
the extraction of deciduous teeth, which may erupt incorrectly as
they are pushed out by permanent teeth, particularly the central
incisors (X01 in the modified Triadan nomenclature system),
which are susceptible to trauma, causing issues with behavior,
feeding, or willingness to accept a bridle and bit (25). Of particular
concern are horses that develop a “wolf tooth,” or first premolar.
This vestigial tooth, which could have been part of either the
permanent or deciduous ancestral dentition, may develop on the
upper jaw, lower jaw, or both. It is situated anterior to the normal
check row and serves no important function in mastication. It
typically erupts during the horse’s first year of life, and it often falls
out on its own by the time an animal reaches around 3 y of age.
Because of its forward position in the mouth, it may interfere with
the normal activity of modern bits and cause pain or tissue damage
(26). As a consequence, it is standard practice for all horses to
have wolf teeth removed at a young age, typically between 1 and
2 y of age (27). Beyond this, many horse dentists also recommend
“flight” of the upper and lower second premolars, a sometimes
controversial practice alternatively referred to as a “bit seat.”
Flotation is used commonly on race and competition horses, and
involves filing off the anterior tooth margin to prevent pinching or
damage of tissues caused by interaction with the bit.

Because hypsodont dentition evolved to handle gritty, low-
quality steppe forage, many dental issues related to occlusion can
be traced to stabling and a diet of nonabrasive plants (24). These
issues are mitigated among freely grazed horses, particularly in
the steppes of northeast Asia, where natural forage wears teeth in
a manner similar to the ancestral caballine diet. Nonetheless,
contemporary Mongolian herders still practice deciduous tooth
extraction. During our ethnographic interviews with individuals
from Khuvsgul province in northern Mongolia and Uvurkhangai
province in central Mongolia, herders reported conducting ex-
tractions of problematic deciduous teeth that were interfering
with animal behavior using pliers. Contemporary herders also
extract wolf teeth during the spring of the animal’s first year using
simple tools, such as a screwdriver (Fig. 1), in conjunction with the
spring roundup and hair-cutting event (28). Although some in-
formants describe this removal in more abstract terms (stating, for
example, that extraction increases the “power” of the horse), we
observed that contemporary Mongol bits cause regular damage
to the anterior margin of the second premolar (SI Appendix, Fig.
S3), meaning that modern bits also interact with wolf teeth when
present. Consequently, wolf tooth extraction plays a practical
role in preventing pain and tissue damage during riding.

![Fig. 1. Mongolian herder removing first premolar, or “wolf tooth,” from a young horse during the spring roundup using a screwdriver. Photo courtesy of D.S.](image-url)
The practice of horse dentistry by contemporary nomadic peoples in Mongolia, coupled with the centrality of horse transport to Mongolian life, both now and in antiquity, raises the possibility that dental care played an important role in the development of nomadic life and domestic horse use in the past. To investigate, we conducted a detailed archaeozoological study of horse remains from tombs and ritual horse inhumations across the Mongolian Steppe, assessing evidence for anthropogenic dental modifications and comparing our findings with broader patterns in horses and nomadic material culture.

Results

Although many of the specimens analyzed (SI Appendix, Table S1) were taphonomically damaged or otherwise incomplete, two of 10 juvenile Bronze Age DSK horses with complete dental preservation displayed unequivocal evidence of anthropogenic modification to the deciduous teeth. These specimens are deciduous incisors: one complete tooth (upper left central incisor/601) and one retained tooth fragment (501/502 or 601/602). They originate from the sites of Uguumur in Zavkhan province, west-central Mongolia (Fig. 2 and Table 1, specimen 014), and the Egiin Gol Valley in east-central Mongolia (Fig. 2 and Table 1, specimen 059). Both teeth display exterior damage to the enamel consistent with attempted removal (Figs. 3 and 4 and SI Appendix, Figs. S4–S6). Although the first specimen, a young (2–2.5 y old) horse from the site of Uguumur in central Mongolia, is fragmented and missing much of the maxillary bone structure, all anterior dentition was present at the time of analysis, with the exception of the upper right deciduous central incisor (Fig. 3, Right). We interpret this as evidence that this tooth had fallen out before the animal’s death, causing the upper left deciduous central incisor (601) to begin to grow medially and orienting the occlusal surface of the tooth at an uncomfortable angle (Fig. 3, Right). This would have caused the animal difficulty with mastication.

The maleruption of this deciduous tooth appears to have prompted an attempted removal or occlusal correction by Late Bronze Age herdiers. The specimen exhibits a triangular notch parallel to the normal occlusal surface of the incisor row (Fig. 3, Right). The modified surface was examined by scanning electron microscopy (SEM) directly under a JEOL JSM-IT100 InTouch-Scope scanning electron microscope. This analysis revealed that the Uguumur tooth was cut through both the enamel and dentine, fraying enamel at the point of first contact and exposing the tooth interior (Fig. 4). SEM also revealed a transverse cut mark on the notch surface in the incisal direction, indicative that the notch was produced through human modification (Fig. 4B). We examined several particles that looked embedded within the exposed dentine using energy dispersive spectroscopy (EDS) (SI Appendix, Fig. S4). The major elements seen in all of the examined particles were indicative of bone or silicate composition. On the basis of current information, it is impossible to say whether these silicate inclusions were introduced naturally through diet or taphonomic processes (e.g., embedded sand). However, the lack of metal residues, which have been identified in Iron Age horse teeth modified by bit use (29), would seem to point toward the use of a stone cutting tool, which may have been efficient at cutting through enamel and dentine. On the basis of the available evidence, it is difficult to say whether the remover intended to saw completely through the crown or whether the removal process might have had additional steps (e.g., breaking the crown off from the root).

A second tooth specimen from the Egiin Gol Valley (a fragment of a deciduous central incisor 501/502 or 601/602, SI Appendix, Fig. S5) also shows apparent modification related to extraction. The specimen appears to have broken during natural tooth eruption, resulting in the retention of a deciduous tooth fragment alongside the permanent dentition that might have similarly caused behavioral or dietary issues in the young (3–4 y old) horse (25). A grooved divot in the tooth’s buccal surface, oriented parallel to the natural occlusal plane and concentrated on a single side of the tooth fragment (SI Appendix, Figs. S5A and S6), may also reflect a cutting motion from the exterior of the horse’s mouth. This perpendicular cutting activity appears to have caused a “slab” or uncomplicated crown fracture (wherein a perpendicular force causes a flat slice of enamel material to separate from the rest of the tooth, but not the pulp cavity). This fracture exposed the underlying dentine (shown by SEM in SI Appendix, Fig. S5B). Unlike the Uguumur specimen, the Egiin Gol horse tooth does not appear to have been sawed by a sharp object. Instead, it exhibits a rounded surface morphology suggestive of a blunt instrument (SI Appendix, Fig. S5C). While some form of developmental enamel defect is also a plausible explanation for this feature, the co-occurrence of an uncomplicated crown (slab) fracture makes this less likely. As
both teeth were recovered in situ, it appears that both removal attempts were unsuccessful or aborted, leaving the damaged incisor fragment in the animal’s mouth until its death and burial. Direct radiocarbon dates on other teeth from these same horses place these early dental procedures at ca. 1150 BCE [mean calibrated (cal.) BCE], or between 1211 and 1056 (2-sigma range) cal. BCE (Table 1). Later specimens from Iron and Middle Age contexts revealed no evidence of similar modifications. Despite this evidence for incisor modification, Bronze Age horses analyzed here exhibited no changes to the first premolar/wolf tooth (X05 in the modified Triadan system). Although many Bronze Age horses were poorly preserved to the point that the alveolar matrix could not be assessed, nearly all of those juvenile specimens with sufficient preservation to assess tooth presence/absence retained a complete wolf tooth (Figs. 5A and 6A). Without human interference, as many as 90% of contemporary yearlings will develop at least one wolf tooth, with between 13% and 32% of animals retaining these teeth into adulthood (25, 26). In the Bronze Age sample, nearly all (n = 9 of 10 total) of the observed specimens younger than 3 y of age with sufficient preservation for assessment displayed an intact wolf tooth of some kind. A single adult specimen, a male horse with an estimated age of 8 y, did exhibit an empty alveolus for a large upper wolf tooth. However, this specimen had experienced obvious postdepositional breakage that

Table 1. Age, dental modifications, taphonomic data, and radiocarbon age/cultural affiliation for key specimens cited in main text

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Estimated age, y (basis)</th>
<th>Dental modifications</th>
<th>Alveolar healing?</th>
<th>Archaeological period/site</th>
<th>Postdepositional alveolar damage?</th>
<th>Laboratory no.</th>
<th>Radiocarbon error range (+/−)</th>
<th>Calibrated age range (2-sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uguumur DS2 F1 (014)</td>
<td>2–2.5 y (eruption)</td>
<td>Sawed deciduous I1</td>
<td>—</td>
<td>DSK</td>
<td>—</td>
<td>GrM11927</td>
<td>2,936</td>
<td>14</td>
</tr>
<tr>
<td>Darkhan Uul Khiirigsuur 75 F2 (059)</td>
<td>3–4 y (eruption)</td>
<td>Sawed deciduous I1</td>
<td>—</td>
<td>DSK</td>
<td>—</td>
<td>GrM11925</td>
<td>2,802</td>
<td>14</td>
</tr>
<tr>
<td>Bor Shoroonii Am SB 2.1.1 (070)</td>
<td>1–2 y (eruption)</td>
<td>Extracted P1 (upper)</td>
<td>Yes (UR, UL)</td>
<td>Slab Burial</td>
<td>No</td>
<td>AA110195</td>
<td>2,545</td>
<td>28</td>
</tr>
<tr>
<td>Bor Shoroonii Am SB 2.1.2 (068)</td>
<td>2–2.5 y (eruption)</td>
<td>Extracted P1 (lower)</td>
<td>Yes (LL)</td>
<td>Slab Burial</td>
<td>No</td>
<td>AA110195</td>
<td>2,545</td>
<td>28</td>
</tr>
<tr>
<td>Bor Shoroonii Am SB 2.1.3 (073)</td>
<td>2–2.5 y (eruption)</td>
<td>Extracted P1 (upper)</td>
<td>Yes (UL)</td>
<td>Slab Burial</td>
<td>Yes (lower jaw only)</td>
<td>AA110195</td>
<td>2,545</td>
<td>28</td>
</tr>
<tr>
<td>Khuiten Gol Delta (Biluuul 2-2) (012)</td>
<td>2–2.5 y (eruption)</td>
<td>Extracted P1 (upper)</td>
<td>Yes (UL, UR)</td>
<td>Pazyryk</td>
<td>No</td>
<td>BETA-308477</td>
<td>2,070</td>
<td>30</td>
</tr>
<tr>
<td>Elt-Ar Burial 14 (079)</td>
<td>1–2 y (eruption)</td>
<td>Extracted P1 (upper)</td>
<td>Yes (UL)</td>
<td>Xiongnu</td>
<td>No</td>
<td>GrM11928</td>
<td>2,002</td>
<td>14</td>
</tr>
<tr>
<td>Airagiin Gozgor Burial 2 (086)</td>
<td>2–2.5 y (eruption)</td>
<td>Chipped lower P2 and extracted lower P1</td>
<td>Yes (LR)</td>
<td>Late Xiongnu</td>
<td>No (maxilla missing)</td>
<td>GrM11864</td>
<td>1,919</td>
<td>13</td>
</tr>
<tr>
<td>Urd Ulaan-Uneet (087)</td>
<td>4–4.5 y (eruption)</td>
<td>P1 worn through bit damage</td>
<td>—</td>
<td>Post-Xiongnu</td>
<td>No</td>
<td>IAAA-170205</td>
<td>1,737</td>
<td>20</td>
</tr>
</tbody>
</table>

Radiocarbon dates were calibrated using IntCAL13 via OxCal. I1, first/central incisor; LL, lower left; LR, lower right; P1, first premolar (wolf tooth); P2, second premolar; UL, upper left; UR, upper right.

Fig. 3. Anthropogenically modified deciduous, upper left first incisor (201) from the site of Uguumur, Zavkhan, central Mongolia, recovered from a ritual horse burial belonging to the Late Bronze Age DSK complex. (Scale bar: 1 square, 1 cm.)
resulted in postmortem (and likely postrecovery) tooth loss. These observed patterns in first premolar persistence suggest that during the Late Bronze Age, wolf teeth were likely present in their natural frequency and that natural processes of wolf tooth loss left a minimal archaeological signature (i.e., few or no empty alveoli with evidence of premortem loss). One explanation for this pattern may be that unextracted wolf teeth undergo natural root resorption.

Bronze Age patterns of wolf tooth retention contrast greatly with the sample of juvenile specimens from the Iron and Middle Ages, in which nearly all of the analyzed juvenile archaeological horse specimens exhibited an empty alveolus (Figs. 5B and 6B). A few of these specimens displayed fracturing or evidence of postdepositional damage, but most had no indication of taphonomic damage to the alveolar bone matrix and many alveoli were still filled with original sediment from excavation at the time of analysis (Fig. 5B and Table 1). Cleaning and alveolar inspection under 20× to 50× magnification with a DinoLITE digital microscope indicated new bone formation in at least one empty alveolus for six of seven specimens from the Early Iron Age (Slab Burial, Pazyryk), Late Iron Age (Xiongnu), and Early Middle Ages (post-Xiongnu) (Fig. 7). New cancellous bone formation replacing the previously smooth alveolar margin is an indicator that the teeth were extracted or otherwise lost before the animal’s death. This is in contrast to evidence of advanced periodontal disease, where teeth become mobile (loose) due to the loss of bony support.

One specimen exhibited a severely damaged deciduous lower second premolar (Fig. 8A, tooth 806) that may provide direct evidence of dental practices. The horse, a juvenile (2–2.5 y old) specimen from the late Xiongnu site of Airagiin Gozgor in central Mongolia, has a large area of exposed dentine with jagged margins on the tooth’s lower anterior surface, near the alveolar margin. Despite postdepositional taphonomic damage to the upper portion of the tooth root, the lower portion of the tooth is undamaged by postdepositional processes (Fig. 8A). The damaged area shows patination and bone remodeling indicative of a predepositional and premortem occurrence. Minor remodeling along the anterior alveolar margin (Fig. 8A) indicates that the tooth was destabilized, and surrounding bone subsequently healed, following trauma to the anterior tooth margin. A radiograph reveals that while no alveolus is visible at the surface, a wolf tooth was originally present in this location (Fig. 8B). The event that detached this tooth fragment was invasive enough to remove or damage a portion of the tooth root. Because of this, we suggest that it was most likely caused by a levering action against the anterior 706 margin during wolf tooth extraction. Although this damage could have
been caused by a different anthropogenic process besides veterinary dental extraction (e.g., traumatic contact with a bit), mandibular wolf teeth are a rare occurrence (26), making the presence of a healed mandibular alveolus in this case a striking coincidence. Moreover, the lower left deciduous premolar, or 706 (opposite the damaged tooth), is intact and undamaged, and the specimen lacks other kinds of toothwear often associated with metal bit use (20, 30). Consequently, we consider anthropogenic damage during wolf tooth extraction to be the most likely cause of this pathology.

The ubiquity of premortem wolf tooth loss among juvenile specimens of varying ages provides a dramatic contrast to the Late Bronze Age sample, and is difficult to explain without invoking human activity. We argue that these patterns are best explained by more frequent tooth extraction during the Early Iron Age and onward, increasing the frequency of empty and partially remodeled wolf tooth alveoli in the archaeological record. Considered alongside evidence for damage directly caused by extraction efforts, our data strongly suggest that the absence of wolf teeth in juvenile horses from Iron and Middle Age contexts was caused by premortem extraction by pastoral herders.

Discussion

Detailed analysis of archaeological horse remains shows that the practice of equine dentistry by nomadic peoples in the Mongolian Steppe can be traced back over 3,000 y, to the period linked with the first evidence for both horseback riding and specialized horse pastoralism in northeastern Eurasia (31–33). Although other explanations for the observed equine dental changes may be possible, indentations to exterior margins of two deciduous incisors from subadult horses appear to indicate the attempted removal of incorrectly erupted milk teeth. In contemporary Western equid dental procedures, deciduous teeth are removed when they begin to erupt incorrectly and interfere with other teeth or affect proper occlusion or feeding behavior (34). However, deciduous tooth extraction is typically performed by using forceps and elevators, the latter of which is a sharp, curved instrument that can be used to separate the tooth from alveolar bone and cut the periodontal ligament and underlying connective tissues (35). In both Late Bronze Age archaeological specimens, the removal procedure appears to have consisted of sawing the crown of the tooth directly from the mouth exterior, presumably using a stone instrument (at least in the case of Uguumur). Removing the upper part of the tooth in this fashion, which leaves the roots intact, would have been a slow, laborious process throughout which the animal would be likely to bite or strike. This technique suggests a kind of experimentation with dental procedures rather than sophisticated knowledge of equine dentition. This pattern is consistent with other
bits which function by applying pressure to the corners of the mouth and provide improved control, made their first appearance in territories immediately adjoining Mongolia during the ninth century BCE. This is demonstrated by archaeological discoveries in Xinjiang, China dated to ca. 850 BCE (33, 41) and Arzhan, Russia dating to ca. 795–815 cal. BCE (42), coeval with the end of the DSK period (7). In Mongolia itself, metal bits first entered the archaeological record in the Early Iron Age, via burials of the Slab Burial or Durvijin Bulsh culture (33). This period witnessed widespread social transformations and perhaps upheaval: Deer stones across Mongolia were uprooted and recycled to build slab burials (43). Three juvenile specimens in our analyzed sample from a single Slab Burial in Bayankhongor, central Mongolia, displayed empty wolf tooth alveoli with evidence of postextraction healing (Table 1). A direct radiocarbon date on one of these specimens dates this feature to ca. 800–551 cal. BCE (2 sigma), with a median age of 753 cal. BCE. The estimated age of these and later Iron and Early Middle Age animals with evidence for dental extraction falls between a tight age range of 1–2.5 y (Table 1), strikingly similar to the average age of 1.4 y reported for modern wolf tooth extraction in some veterinary reports (27). The coincident timing between the regional appearance of metal bits and the initiation of wolf tooth extraction suggests that the adoption of metal bit technology prompted innovations in equine dental practice, which had been initiated, perhaps for the first time, by nomadic herdsmen living in Mongolia several centuries before.

Like the controversial Buten horse (44), many of our analyzed Iron and Middle Age specimens display a kind of damage or modification to the occlusal surface of the second premolar (X06 in the modified Triadan nomenclature system) referred to as bit wear (20), which has been described elsewhere (9). Although this kind of wear could conceivably be caused by intentional dental filing similar to modern flotation (23, 45), the occlusal wear observed in our Iron Age and Early Middle Age samples was accompanied by other kinds of damage that are more definitively indicative of contact between the bit, teeth, and mandibular bone (9), including damage to the anterior margin of the second premolar (30) and new bone formation at the corners of the mouth where a jointed bit would rest. Bit wear was also entirely absent from the DSK sample, corroborating evidence from early horse equipment for Late Bronze Age organic bit use (9, 38). Critically, then, the paired emergence of both metal bits and metal bit wear in the archaeological record of the Early Iron Age supports the inference of a link between metal bit use and the initiation of wolf tooth extraction.

One early Middle Age horse specimen, a mummy from Urd Ulaan-Uneet (SI Appendix, Fig. S7), provides some additional insights into the relationship between first premolar removal and bit use. This animal has a single, large retained upper wolf tooth that displays occlusal beveling caused by a metal bit. The occlusal damage to this specimen is indicative that, when unextracted, wolf teeth would interact directly with the jointed metal snaffle bits used in antiquity. Considered together, the simplest interpretation of these patterns is that the use of metal bits caused new challenges...
related to interaction with and damage to the first premolar, prompting the development of wolf tooth removal as a cultural practice in northeast Asia.

This Late Bronze Age dental modification counts among the earliest documented instances of equine veterinary care, and the oldest known evidence for horse dentistry. At first glance, the detailed historical record of early equine veterinary care in places such as China, Greece, Rome, and Syria, which spans the late second millennium BCE through the early centuries CE (11, 15, 16), might imply that equine dentistry emerged in the sedentary civilizations of the Old World. However, the earliest textual references describe only nonsurgical medicinal treatments and make few mentions of oral health (11). Recent archaeological discoveries suggest that human care of domestic animals was practiced by hunter-gatherers as far back as the Paleolithic (46), and that pastoralists may have occasionally practiced surgical procedures on domestic animals as early as the Neolithic in Europe (47). The evidence presented here indicates that horse dentistry was developed by nomadic pastoralists living on the steppes of Mongolia and northeast Asia during the Late Bronze Age, concurrent with the local adoption of the metal bit and many centuries before the first mention of dental practices in historical accounts from sedentary Old World civilizations.

Our results reveal a fundamental link between equine dentistry and the emergence of horsemanship in the steppes of Eurasia. At the turn of the first millennium BCE, militarized, horse-mounted peoples reshaped the social and economic landscape of many areas of the Eurasian continent. Conflagrations with equestrian peoples, such as those between the Persian Empire and the Pontic “Scythians,” plagued alluvial civilizations from the Near East to India and China, while large-scale movements of people linked East and West in never-before-seen ways (48). The archaeological and historical records indicate that the earliest horseback riding was accomplished without stirrups or saddles, and probably using only bitless or organic-mouthpiece bridles (49, 50). The bronze snaffle bit, and the improved control it provided, was a key technological development that enabled the use of horseback riding for more stressful and difficult activities, such as long-distance transportation and warfare (32). We argue that these technological improvements in horse control were preceded and sustained by innovations in veterinary dentistry by nomadic peoples living in the continental interior. By increasing herd survival and mitigating behavioral and health issues caused by horse equipment, innovations in equine dentistry improved the reliability of horseback riding for ancient nomads, enabling horses to be used for nonpastoral activities like warfare, high-speed riding, and distance travel.

Conclusion

Archaeozoological data from Mongolian horses indicate that the nomadic practice of equine dentistry dates back more than 3,000 y to the DSK complex, a Late Bronze Age culture associated with the first mounted horseback riding and mobile pastoralism in eastern Eurasia. Attempted removal of deciduous incisors through sawing of the exterior suggests experimentation with dental extraction, but not the removal of wolf teeth. The appearance of extracted first premolars in the first millennium BCE coincides with the arrival of metal bits in the archaeological record and oral trauma linked with metal bit use, suggesting that innovations in dental practice were an adaptation to the mechanical changes in horse equipment. These bronze and metal bits provided greater control over the horse, facilitating the development of military uses for the horse, but also introduced new dental problems with the first premolar. Our results indicate that, coincident with the earliest evidence for metal bit use, wolf tooth extraction was practiced in Mongolia by ca. 750 BCE and continued through the early Middle Ages (Table 1). These results push back the earliest dates for equine dentistry by more than a millennium and suggest that nomadic peoples developed key adaptations in veterinary care that enabled more sophisticated horse equipment, ultimately changing the structure of communication, exchange, and military power in ancient Eurasia.

Materials and Methods

We conducted a detailed study of archaeological horse collections spanning the past 3,200 y, including those from the Late Bronze Age DSK complex (ca. 1200–700 BCE, n = 70), Early Iron Age Slab Burial culture (ca. 700–300 BCE, n = 4), Pazyryk culture (ca. 600–200 BCE, n = 2), Late Iron Age Xiongnu Empire (ca. 200 BCE–200 CE, n = 3), Early Middle Ages post-Xiongnu period (ca. 100–550 CE, n = 3), and Turkic Khaganate (ca. 600–800 CE, n = 3). This assemblage comprises all archaeological horse remains in collections at the National Museum of Mongolia. The greater number of individual horse burials from the Bronze Age sample arises from the fact that these animals were inhumed in small, relatively shallow burials that are found in large numbers around monuments of this era (5, 6), while animals from other periods are primarily recovered from within human burials. For each specimen, we estimated age and sex using dental eruption schedules (51), incisor wear patterns (52), and crown height wear curves (53). We analyzed all teeth and alveolar margins from each specimen under low-power (20×) and high-power (200×) magnification for evidence of human modification, including mechanical changes to the tooth surface and evidence of tooth extraction (missing dentition, damage to tooth margin or alveolar bone, or alveolar tooth fronting). For juvenile specimens lacking a first premolar but with an intact alveolus present, we carefully brushed the alveolar surface using brushes and a small air blader, and examined the alveolar cavity under 20× to 50× magnification, using a DinoLITE Premier digital microscope for evidence of bone remodeling and healing, to identify evidence for healing indicative of premortem extraction or loss. Specimens with apparent modifications were sampled for radiocarbon dating (using an unmodified intact tooth from the same specimen). Direct radiocarbon dates were calibrated using OXCAL and the IntCal13 calibration curve, and are reported in Table 1.

Two specimens displaying apparent human modifications were examined directly under a JEOL JSM-IT100 IntTouchScope scanning electron microscope at the Max Planck Institute for the Science of Human History. The specimens were viewed uncoated in backscattered electron mode under low vacuum at 10 kV. Specimens were also tilted up to 18° to view different surfaces of the modified teeth (Figs. 4 and 5). Particles that looked embedded within the modifications were examined with EDS using the built-in JEOL Dry Extra EDS detector. EDS analysis, in this case, was qualitative (i.e., nonquantitative), and the major elements seen in all of examined particles were indicative of bone or silicate particles (SI Appendix, Fig. 54).

Finally, we considered these data alongside taphonomic evidence (including the completeness of each specimen, state of curation, and evidence of postdepositional damage) to assess implications for ancient human activity (reported in SI Appendix, Table S1). We compared our inferences with the archaeological record for horse bridling and tack (38) to evaluate the contribution of changes in horse equipment and use to observed dental patterns. All data collected in the analysis are provided in SI Appendix.

ACKNOWLEDGMENTS. We thank Dr. Rodney Flint Taylor and Dr. Dave Fly for their valuable input on equine dentistry, Dr. Gantuya and Dr. Justin Woolsey (Enerekh Animal Hospital, Ulaanbaatar, Mongolia) for their assistance with radiographs, and the National Museum of Mongolia and the American Center for Mongolian Studies in Ulaanbaatar for facilitating this research. This research was funded, in part, by National Geographic Society Young Explorer’s Grant 9713-15, Fulbright US Student Research Program Grant 34154234, and the US Embassy in Mongolia’s Ambassador’s Fund for Cultural Heritage Preservation. Additional funding was provided by the Max Planck Institute for the Science of Human History.


www.pnas.org/cgi/doi/10.1073/pnas.1721189115

Taylor et al.
52. Academy of Equine Dentistry (2013) Teeth of the Horse-Chart for Accurately Telling the Age from Six Months to Twenty-Nine Years (Academy of Equine Dentistry, Glens Ferry, ID).