

Variations in the oral health of millet agriculturalists in the northern ‘Great Wall’ region of China from the Middle Neolithic to the Sixteen Kingdoms period

Kenji OKAZAKI^{1*}, WEI Dong¹, ZHU Hong¹

¹*Research Center for Chinese Frontier Archaeology, Jilin University, Changchun, China*

Received 1 August 2012; accepted 29 September 2013

Abstract Variations in oral paleopathology have been widely documented among groups stemming from different regions or periods to clarify the relationship between human health and type of subsistence. The skeletal materials unearthed around the Great Wall in northern China are suitable for this aim since archeological studies minutely report the changes in subsistence in the area. We examined oral health in the skeletal assemblages of nine millet agricultural groups between the Middle Neolithic period (c. 3800–2800 BC) and the Sixteen Kingdoms period (304–439 AD) around the Great Wall of China, and found a consistent increase in the prevalence of caries over time. Although this finding is based on analysis without sufficient demographic data, the statistically similar age distribution among the groups suggests a minimum effect of sampling error. Further analysis using three groups that have a relatively large sample size for each sex and age category also showed an increase in caries, antemortem tooth loss, periapical abscess, and calculus prevalence, and a decrease in advanced attrition, suggesting an increased consumption of agricultural foods. This trend could be a result of a more tender/refined diet related to the development of food-processing techniques, which have been demonstrated by archaeological/historical evidence and stable isotope analyses. On the other hand, sex differences in oral health varied between the Jiangjialiang Middle Neolithic and the Tuchengzi Warring States samples. In the Middle Neolithic assemblage, the frequency of advanced dental attrition in males was 3-fold that of females, suggesting the sexual division of labor in this period. In contrast, in the Warring States assemblage, the prevalence of caries in young males was a quarter of that in young females, reflecting the difference of living environments between the sexes, where young males were probably under military conscription at that time.

Key words: dental caries, advanced attrition, sex differences, Late Neolithic/Early Dynasty period, Spring and Autumn/Warring States period

Introduction

The purpose of this study is to document and interpret variations in oral health among millet agriculturalists whose type of subsidiary economies varied (e.g. hunting-gathering, animal herding, and wheat agriculture). This study specifically aims to examine the factors contributing to group and sex differences in oral disease using human skeletal remains derived from nine archaeological sites dating from the Middle Neolithic, Late Neolithic/Early Dynasty (Xia and Shang) (3000–1046 BC), Spring and Autumn/Warring States (770–221 BC), and the Sixteen Kingdoms periods around the Great Wall of China (Table 1).

Oral pathology is a method utilized by biological anthro-

pologists worldwide to assess diet and food-preparation techniques in past societies because these activities are strongly related to subsistence patterns (Turner, 1979; Powell, 1985; Lukacs, 1989; Walker and Erlandson, 1986; Walker and Hewlett, 1990; Larsen, 1997; Temple and Larsen, 2007; Oyamada et al., 2010). Lukacs (1989) proposed a ‘dental pathology profile’ (DPP) to standardize the recording and reporting of dental pathological conditions for comparative research. The variables in DPP include caries, antemortem tooth loss (AMTL), periapical abscess, alveolar resorption, calculus, and severe attrition. The components of the DPP shift from hunting-gathering to agriculture: intensive agriculturalists typically have higher frequencies of these components except severe attrition (unless abrasive materials were mixed with the food during preparation) compared to hunter-gatherers. Hunter-gatherers do not necessarily have lower frequencies of AMTL and periapical abscesses, because caries as well as severe attrition can cause both pathologies. Calculations by Turner (1979) concerning average prevalence of dental caries based on a worldwide population study showed a prevalence of 1.3% in

* Correspondence to: Kenji Okazaki, Department of Anatomy, Faculty of Medicine, Tottori University, 86 Nishi-cho, Yonago 683-8503, Japan.
E-mail: ken_okz@med.tottori-u.ac.jp

Published online 29 November 2013
in J-STAGE (www.jstage.jst.go.jp) DOI: 10.1537/ase.130929

Table 1. The approximate chronology of northern China

Early Neolithic (Yangshao)	c. 5000–3000 BC
Middle Neolithic ^a	c. 3800–2800 BC
Late Neolithic (Longshan)	c. 3000–2000 BC
Xia Dynasty	c. 2070–1600 BC
Shang Dynasty	c. 17 century BC–1046 BC
Western Zhou Dynasty	1046–BC 770 BC
Spring and Autumn/Warring States (Eastern Zhou Dynasty)	770–221 BC
Qin Dynasty	221–206 BC
Han Dynasty	206 BC–220 AD
Three Kingdoms	220–280 AD
Western Jin Dynasty	280–316 AD
Sixteen Kingdoms	304–439 AD

^a Designated as the period of transition from Yangshao to Longshan.

a foraging economy, 4.8% in a mixed economy, and 10.4% in an agricultural economy.

The zone from south-central Inner Mongolia to the western Liaoning province (Liaoxi) is characterized by conflicts between two large-scale civilizations (nomadic peoples and Chinese states). A series of Chinese dynasties from Zhou to Ming repeatedly built and repaired long walls to protect their territory from invasion by nomadic peoples (Chang, 1977; Miyamoto, 2000, 2005; Di Cosmo, 2002). This contact zone is archaeologically referred to as the ‘Great Wall Region,’ the middle and lower reaches of the Yellow River are referred to as the ‘Central Plains,’ and the region from the Great Wall Region northward is referred to as the ‘Northeastern Steppe Area.’ Changes in subsistence patterns in the Great Wall Region during the transition between the Neolithic and the Sixteen Kingdoms period are characterized as follows: (i) the beginning of millet cultivation with an increasingly warm and wet climate in the Early Neolithic period (Tian and Shi, 1991; Miyamoto, 2000, 2005; Jin, 2004); (ii) the advent of animal herding with an increasingly cooling and dry climate during the Late Neolithic (Longshan) period and Early Dynasty period (Chang, 1977; Miyamoto, 2000, 2005; Di Cosmo, 2002; Jin, 2004; Honeychurch and Amartuvshin, 2006); (iii) the introduction of wheat cultivation beginning in the Late Neolithic period and its subsequent spread (Crawford, 2006; Gu, 2007; Dong et al., 2007); (iv) the rise of farming productivity with the spread of advanced agricultural technologies and theories between the Warring States and the Sixteen Kingdoms periods (Chang, 1977; Liu, 2001; Luo, 2001).

In China, a limited number of studies demonstrate relatively low frequencies of caries among skeletal samples dating from the Neolithic to Early Dynasties (Mao and Yan, 1959; Turner, 1979; Li and Huang, 1991; Sakashita et al., 1997; Pechenkina et al., 2002, 2007; Todaka et al., 2003; Zhang, 2003; Eng, 2007; Zhang et al., 2009; Liu et al., 2010). In the Central Plains, an increase in oral disease and

systemic stress and a decrease in the degree of dental attrition did not occur until the Late Neolithic (Longshan) period, (c. 3000–2000 BC) (Pechenkina et al., 2002, 2007), although stable isotope analyses indicate that the degree of millet agriculture was already relatively intensive in the Early Neolithic (Yangshao) period, (c. 5000–3000 BC) (Cai and Qiu, 1984; Pechenkina et al., 2005). Deteriorations in oral health beginning in the Longshan period were likely associated with the intensification of millet agriculture triggered by a decrease in environmental resources due to climatic cooling (Pechenkina et al., 2002, 2007). These deteriorations in oral health might be temporary, because the prevalence of caries among people of the Yin-Shang dynasty (c. 1700–1046 BC) was considerably low (Turner, 1979; Sakashita et al., 1997; Todaka et al., 2003). Differences in caries prevalence among the groups during the transition between the Bronze Age and early Iron Age in the Great Wall Region were approximately 3–5% for two groups of the nomadic economy, 6–10% for three groups of the mixed economy, and 12–18% for two groups of the agricultural economy (Zhang et al., 2009). This indicates that the relationship between caries prevalence and subsistence pattern in the populations of the Great Wall Region followed predictions made by Turner (1979). On the bases of these previous research efforts, we developed the following hypothesis for the present study: the prevalence of oral disease among agriculturalists should increase with time due to the development of agricultural productivity and food-processing techniques in the Great Wall Region, even though the types of subsistence followed and the degree of dependence on them varied among the sites, as explained below.

Materials

Samples and the environment settings

A total of 8444 teeth from 496 individuals obtained from six sites in the Great Wall Region were included in the study: Jiangjialiang and Miaozigou during the Middle Neolithic period, Zhukaigou during the Late Neolithic/Early Dynasty period, Tuchengzi and Yinniugou during the Warring States period, and Lamadong during the Sixteen Kingdoms period (Table 2, Figure 1). Three assemblages from previous studies were used for comparative data: Dadianzi during the Late Neolithic/Early Dynasty, and Maoqinggou and Jiangjiongou during the Spring and Autumn/Warring States period (Inoue et al., 1997; Zhang et al., 2009) (Table 2, Figure 1). In total, the nine assemblages between the Middle Neolithic and the Sixteen Kingdoms periods were selected as millet agriculturalists with varying degrees of reliance on agriculture and subsidiary economies in the Great Wall Region. All six collections studied by the authors are curated at the Research Center for Chinese Frontier Archaeology of Jilin University.

Jiangjialiang site

The site is located at Yangyuan in the northwestern Hebei province. The Sanggan River passes near the site. Jiangjialiang is archaeologically situated at the boundary line between the Yangshao culture range and the Hongshan culture range (Hebei Provincial Institute of Cultural Relics,

Table 2. Sites, sample size and mean ages at death

Samples around the Great Wall ^a	Map no.	Location	Reference	Date ^b	Sample size			Mean age (years)
					Individuals	Alveoli	Teeth	
Jiangjialiang	A	Northern Hebei	This study	6850–4850 BP	79	2216	1551	35.0
Miaozigou	B	South-central Inner Mongolia	This study	5800–5000 BP	10	300	147	31.1
Zhukaigou	C	South-central Inner Mongolia	This study	4200–3500 BP	25	580	238	37.9
Dadianzi	D	Southeastern Inner Mongolia	Inoue et al. (1997)	4000–3500 BP	152	—	2752	—
Maoqinggou	E	South-central Inner Mongolia	Inoue et al. (1997)	770–221 BC	19	—	457	—
Tuchengzi	E	South-central Inner Mongolia	This study	403–206 BC	121	3502	2301	36.9
Yinniugou	E	South-central Inner Mongolia	This study	403–221 BC	27	724	434	36.7
Jiangjungou	E	South-central Inner Mongolia	Zhang et al. (2009)	403–221 BC	—	—	292	—
Lamadong	F	Western Liaoning	This study	289–370 AD	234	6451	3773	35.8

^a Mandarin Chinese names were spelled in accordance with the Pinyin system.

^b Dates were expressed in two forms because dating methods are different: Christian era for the date on the basis of historical documents, before present for radiocarbon dating.

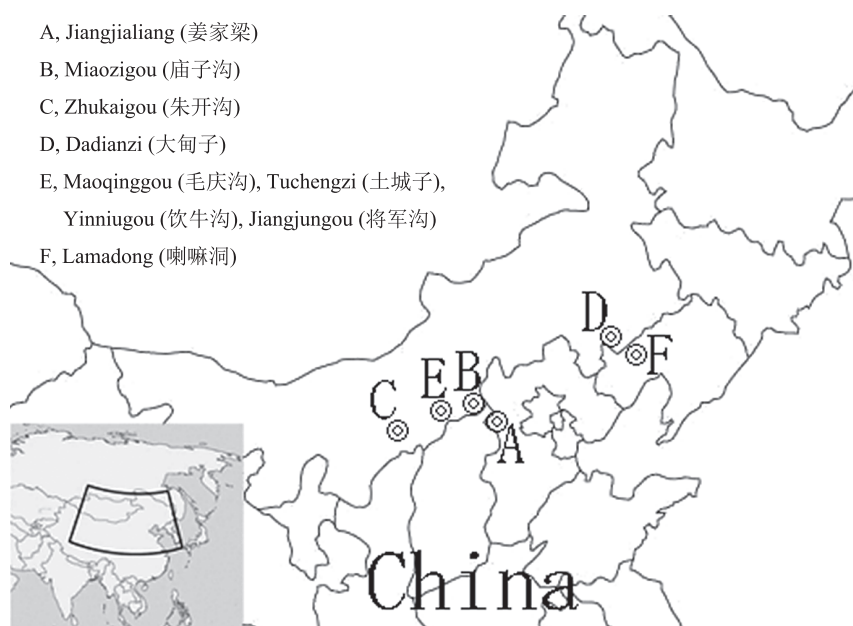


Figure 1. Map showing the geographic locations of the nine mortuary sites around the Great Wall of China.

2001). Nine house foundations and 78 tombs were unearthed at the first section, while more than 29 tombs were found at the second and third sections of the site (Hebei Provincial Institute of Cultural Relics, 2001; Li, 2008). The volume of grave goods varied from nothing to five among individual burials, which might suggest the existence of a social ranking system at that time. Spinning wheels were unearthed with females and axes with males, which could suggest a sexual division of labor (Hebei Provincial Institute of Cultural Relics, 2001).

The date of this site was estimated at around 6850 ± 80 BP (uncalibrated) by the radiocarbon dating method using carbide unearthed from the house foundations (Hebei Provincial Institute of Cultural Relics, 2001). However, the date of the burials is thought to be more recent than that of the houses because parts of the house foundations were crosscut by the construction of the burials. The burial culture of the Jiangjialiang site is very similar to that of the Danangou site

in Inner Mongolia, which is assigned to the Xiaoheyuan culture (c. 4850 years ago). Accordingly, the date of the Jiangjialiang tombs corresponds to the transition from the Yangshao culture to Longshan culture (c. 6850–4850 BP) (Hebei Provincial Institute of Cultural Relics, 2001).

Miaozigou site

The site is located on Uraharura, Qahar Youyi Qianqi in south-central Inner Mongolia at the south coastal region of Huangqihai Lake. Fifty-two dwellings, 139 ash pits, and 42 tombs were unearthed (Inner Mongolia Institute of Cultural Relics and Archeology, 2003). The large amount of production tools suggest that the main subsistence pursuits involved primitive agriculture, although hunting/fishing, gathering as well as some animal herding also played a considerable part (Inner Mongolia Institute of Cultural Relics and Archeology, 2003). The animal remains unearthed from the site included various mammals, birds, and aquatic

molluscs, and 23.3% of these animal remains could have been domesticated animals (pigs and dogs) (Inner Mongolia Institute of Cultural Relics and Archeology, 2003). This site dates between 5800 and 5000 BP (calibrated) according to six radiocarbon dating results (Inner Mongolia Institute of Cultural Relics and Archeology, 2003).

Zhukaigou site

The site was discovered in Ejina Banner of the Inner League in south-central Mongolia. Eighty-three house foundations, 207 ash pits, and 348 tombs were unearthed. The radiocarbon dating method and the stratigraphical relationship indicate that the site lasted between 4200 and 3500 BP (calibrated), roughly coinciding with the late Longshan culture and the early Shan dynasty period (Archaeological Institute of Inner Mongolia and Ordos Museum, 2000). Among 495 production tools excavated from this site, 36.2% were utensils, 34.4% were agricultural instruments, 15.2% were spinning and sewing tools, and 14.2% were hunting/pastoral tools and weapons. Comparing these frequencies among the five age stages, the frequency of the agricultural instruments gradually decreased over time, and is thought to have resulted in a semi-agricultural and semi-pastoral economy in the late stages (Archaeological Institute of Inner Mongolia and Ordos Museum, 2000). Among 157 mammal remains excavated in this site, 35.7% were sheep, 33.1% were pigs, and 15.3% were cattle. The morphology and age distribution indicate that these three kinds of mammals could have been fully domesticated at this site (Huang, 1996). Finally, the individuals with a large number of grave goods and sacrifices tended to be interred in larger tombs, which might suggest that the social class was highly stratified at this site (Archaeological Institute of Inner Mongolia and Ordos Museum, 2000).

Tuchengzi site

The site is located on Helingeer in south-central Inner Mongolia. The cemetery is found around the ruins of fortress walls. Through nine excavations from 1997 to 2005, over 2000 tombs were unearthed from a 1.5 million square meter area (Inner Mongolia Institute of Cultural Relics and Archeology, 2006). The human skeletal remains unearthed from the tombs of the Warring States and Qin Dynasty periods (221–206 BC) were used in this study. The grave goods mainly consisted of potteries, bronze or iron accessories and weapons, and copper coins (Inner Mongolia Institute of Cultural Relics and Archeology, 2006). Some of the burial individuals were missing their crania or lower limbs. Arrowheads made of copper or bones were occasionally found with the buried individuals (Inner Mongolia Institute of Cultural Relics and Archeology, 2006).

Yinniugou site

The site is located at Ulanqab in south-central Inner Mongolia. A joint team of local Chinese and Japanese archaeologists carried out the excavation. This site is 1 km from the Maoqinggou site, and both sites are known as cemeteries for people who were part of the northern style bronze culture (Inner Mongolia Institute of Cultural Relics and Archeology and Japan Kyoto Society of Chinese Archaeology,

2001). This site existed between the middle and final stages of the Warring States period, while the Maoqinggou site existed between the Spring/Autumn period and the late stage of the Warring States period according to the seriation of the bronze belt hooks unearthed from both sites. Accordingly, the two sites coincided during the middle and late stages of the Warring States period (Inner Mongolia Institute of Cultural Relics and Archeology and Japan Kyoto Society of Chinese Archaeology, 2001).

Lamadong site

The site is located at Beipiao in the western Liaoning province. About 4000 grave goods were unearthed, which consisted of pottery, accessories or tools made of iron, bronze, gold, silver, and bone from 353 tombs (Liaoning Institute of Cultural Relics and Archeology, 2004). While the grave goods of the Lamadong site basically reflect the culture of the Xianbei people, they are significantly influenced by the culture of the Central Plains accompanied by the sinicization of the Xianbei people and the culture of the Fuyu people, who dwelt close to the Xianbei people (Chen, 2009). Based on the consistency between the cultural patterns of grave goods and historical records, the tombs should be dated between 289 AD, when the chief of the Xianbei people (Murong Hui) transferred the capital to the great Ling river basin, and 370 AD, when the First Yan dynasty collapsed (Liaoning Institute of Cultural Relics and Archeology, 2004).

Methods

Oral pathology

The presence of AMTL, carious lesions, periapical abscess, alveolar resorption, calculus accretion, and the degree of dental wear were examined in each tooth using a 10 × magnifying lens and a dental mirror in accordance with standards established by Lukacs (1989) and Hillson (1996, 2001). AMTL was defined as a completely closed alveolar socket with reduced alveolar height to a nearly closed alveolar socket with active bone formation (Lukacs, 1989; Pechenkina, personal communication). Carious lesions were identified based on enamel demineralization in stages that ranged from complete destruction of a tooth crown to pinprick sized lesions (Lukacs, 1989; Hillson, 1996; Temple and Larsen, 2007). Carious lesions were classified as: (1) occlusal surface, (2) interproximal surfaces, (3) smooth surfaces, (4) cervical, (5) root, and (6) large carious lesions (Buikstra and Ubelaker, 1994). Periapical abscesses originate as a chronic cyst and/or an infection in the pulp due to chronic cariogenesis, severe wear, or dental trauma. Because of the difficulty in differentiating between both factors (Dias and Tayles, 1997; Oxenham et al., 2006), only the presence or absence of periapical abscess was recorded (Lukacs, 1989). Alveolar resorption also has a multifactorial etiology (e.g. periodontal disease, caries, periapical abscess, and continuous eruption) (Hillson, 1996; Kaifu et al., 2003). Although making a correct diagnosis for alveolar resorption is difficult, the following definitions were all counted as affected: (1) slight: resorption confined to the alveolar crest with active bone formation or periodontal pocket or notch-

like resorption of the alveolar crest; (2) moderate: horizontal or vertical bone loss that is limited to half of the length of the tooth root; (3) severe: horizontal or vertical bone loss that reaches more than half of the length of the tooth root (Lukacs, 1989; Sakashita et al., 1997; Pechenkina, personal communication). Calculus accretion on tooth crowns and roots near the cervix was graded from small to large according to standards defined by Brothwell (1981). These three stages were all counted as affected in this study.

Given that dental wear has an important etiological role in oral pathology, it is important to compare a measure of this variable among the samples (Lukacs, 1989). Tooth wear was scored according to standards established by Buikstra and Ubelaker (1994) using primary scores for the anterior and premolar teeth, and summary scores were derived from all quadrants of the molar teeth. Advanced wear was defined as a score exceeding seven points in the anterior and premolar teeth, over 35 points in the molar teeth, as well as noncarious pulp exposure.

Controlling for biological sex and age

Oral disease frequency is expected to be higher in older age groups since most pathological conditions are progressive. Therefore, differences in age distribution among the six assemblages studied by the authors were examined before executing the group comparison. Regarding the three assemblages of Jiangjialiang, Tuchengzi, and Lamadong, the frequencies of pathological conditions were calculated for each age group and biological sex since these assemblages have a relatively large sample size with the corresponding postcranial bones effectively assisting in sex and age estimation. The age and sex of each individual were determined based on the standards of Buikstra and Ubelaker (1994).

Adult age was estimated based on age-related changes in the morphology of pubic symphysis and auricular surfaces (Todd, 1920; Lovejoy et al., 1985; Meindl et al., 1985). Cranial suture closure was used to estimate age where pelvic bones were unavailable (Meindl and Lovejoy, 1985). The patterns of skeletal epiphyseal closure and tooth eruption were used to estimate age among subadults (Ubelaker, 1989; Scheuer and Black, 2004). Only two age categories were defined in order to maintain statistical power: Young (13–35 years) and Old (over 35 years). Sex was determined based on pelvic morphology (Buikstra and Ubelaker, 1994). Crani-

al morphological traits were used when pelvic bones were not recovered (Buikstra and Ubelaker, 1994).

Calculations and statistical treatments

The ratio of observable teeth was lower in the anterior dentition due to taphonomic factors influencing tooth preservation. Therefore, the tooth count method was used for calculation in order to avoid bias caused by imbalance among teeth segments (Douglas, 2006). Namely, the prevalence for carious teeth, calculus, and advanced attrition was calculated as affected teeth/observable teeth $\times$ 100. The prevalence of AMTL, pericapical abscess, and alveolar resorption was calculated as affected alveoli/examined alveoli $\times$ 100.

Regarding the three assemblages that have relatively large sample size, the sex, age, and group differences of frequencies calculated by the tooth count manner were examined by Yates' chi-squared test, since this method is best applicable to larger sample sizes. Bonferroni correction was used for multiple comparisons when the group differences were examined. The differences in the age distribution among the assemblages were examined by analysis of variance, and multiple comparisons were made using Tukey's HSD test. These analyses were performed using the computer program package STATISTICA (StatSoft Inc., 1996).

Results

Group differences

The age distribution was not statistically different among the six assemblages by analysis of variance or the following multiple comparison (Table 2). Table 3 indicates group differences in oral disease frequencies among the nine assemblages including comparative data. Figure 2 shows group differences focusing on both caries and AMTL, since both were available in comparative data. The frequency of caries increased with each subsequent era, while the AMTL frequency varied relatively randomly. Regarding caries frequency, the ratio of interproximal lesions was nearly 50% in all of the assemblages (crown, interproximal surfaces, cervical and root, large lesion: Jiangjialiang 35.0%, 52.5%, 10.0%, 2.5%; Tuchengzi 5.0%, 50.6%, 27.6%, 16.7%; Lamadong 17.4%, 49.4%, 17.6%, 15.6%, respectively).

Figure 3 shows the group comparisons of each oral disease frequency among the three assemblages of Jiangjialiang,

Table 3. Oral diseases summary: six samples studied by the authors and three comparative data

Samples around the Great Wall	Caries ^a	Antemortem tooth loss ^b	Periapical abscess ^b	Alveolar resorption ^b	Calculus ^a	Advanced attrition ^a	Reference
Jiangjialiang	2.6 (1551)	4.8 (2216)	1.6 (2015)	8.5 (2015)	40.5 (1450)	5.5 (1551)	This study
Miaozigou	2.7 (147)	0.3 (300)	0.0 (300)	0.0 (300)	27.6 (145)	0.0 (147)	This study
Zhukaigou	7.1 (238)	7.7 (534)	2.0 (546)	4.8 (546)	51.1 (235)	4.2 (238)	This study
Dadianzi	6.4 (2752)	5.3 (4768)	—	—	—	—	Inoue et al. (1997)
Maoqinggou	10.7 (457)	7.2 (880)	—	—	—	—	Inoue et al. (1997)
Tuchengzi	10.6 (2301)	4.8 (3502)	2.1 (3305)	5.1 (3305)	54.8 (2259)	3.7 (2301)	This study
Yinniugou	12.2 (419)	12.4 (724)	5.1 (631)	9.0 (631)	50.1 (399)	6.9 (419)	This study
Jiangjiongou	17.8 (292)	—	—	—	—	—	Zhang et al. (2009)
Lamadong	13.4 (3773)	9.4 (6451)	3.6 (5758)	6.2 (5758)	71.2 (3673)	4.2 (3773)	This study

^a % affected teeth (sample size).

^b % affected alveoli (sample size).

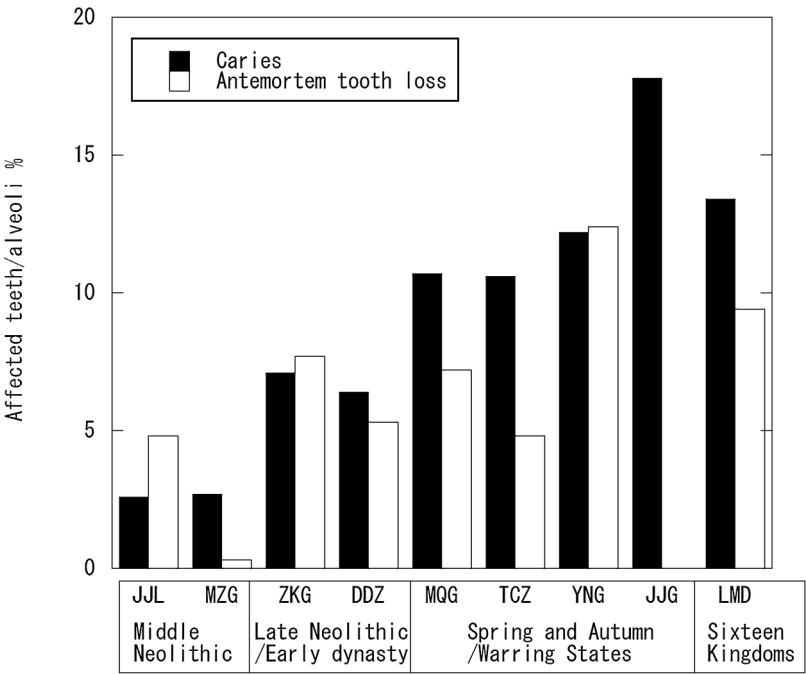


Figure 2. Percentage differences in dental caries and antemortem tooth loss among assemblages. Abbreviations: JJL, Jiangjialiang; MZG, Miaozigou; ZKG, Zhukaigou; DDZ, Dadianzi; MQG, Maoqinggou; TCZ, Tuchengzi; YNG, Yinniugou; JJG, Jiangjungou; LMD, Lamadong. The antemortem tooth loss prevalence of the Jiangjungou Warring States assemblage has not been reported.

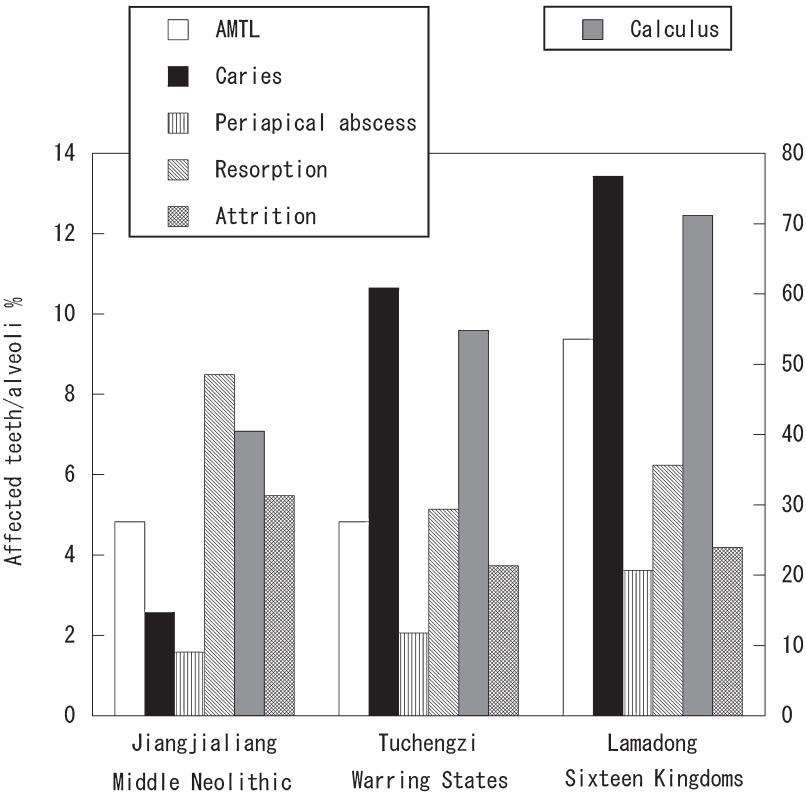


Figure 3. Percentage differences in the six items of oral disease among assemblages.

Tuchengzi, and Lamadong, each of which has a relatively large sample size. Detailed group comparisons for each sex and age category are described in Table 4, Table 5, Table 6,

Table 7, Table 8, and Table 9. For the Jiangjialiang Middle Neolithic assemblage, the frequencies of AMTL (total 4.8%), periapical abscess (total 1.6%), dental calculus (total

40.5%), as well as dental caries were lower compared to the Lamadong Sixteen Kingdoms assemblage ($P < 0.001$, Table 5; $P < 0.001$, Table 6; $P < 0.001$, Table 8, respectively). In contrast, the frequencies of advanced attrition (total 5.5%) and alveolar resorption (total 8.5%) were higher in the Jiangjialiang Middle Neolithic assemblage compared to the other two historical assemblages ($P = 0.048$, Table 9; $P = 0.001$, Table 7, respectively). In particular, the advanced attrition frequency of the Jiangjialiang Middle Neolithic young males (total 8.1%) was much higher than both historical young males (total 1.2%, total 2.4% respectively, $P < 0.001$, Table 9). Although the dental caries frequency in the Tuchengzi Warring States assemblage was higher than the Jiangjialiang Middle Neolithic assemblage ($P < 0.001$, Table 4), there was little difference in the AMTL and periapical abscess frequencies between both groups (Table 5, Table 6). Finally, the frequencies of AMTL (total 9.4%), periapical abscess (total 3.6%) calculus accretion (total 71.2%), and dental caries (total 13.4%) were highest in the Lamadong Sixteen Kingdoms assemblage ($P < 0.001$, Table 5; $P < 0.001$, Table 6; $P < 0.001$, Table 8, respectively).

Sex differences

The pattern of sex differences was different in the Middle Neolithic assemblage compared to the other two historical assemblages (Tuchengzi and Lamadong). The latter two historical assemblages displayed higher frequencies of AMTL and caries and a slightly lower frequency of calculus in fe-

males, and mostly equal frequencies of periapical abscess, alveolar resorption, and advanced attrition between both sexes (Table 4, Table 5, Table 6, Table 7, Table 8, and Table 9). In contrast, the Jiangjialiang Middle Neolithic assemblage showed a higher frequency of advanced attrition and a slightly lower calculus frequency in males, and a mostly equal caries frequency (Table 4, Table 8, and Table 9).

Figure 4 shows sex differences in the frequency of caries. In the Tuchengzi Warring States assemblage, the caries frequency of young females was four times higher than that of young males (young females 7.3%, young males 1.8%, $P < 0.001$, Table 4). Figure 5 shows sex differences in advanced attrition. In the Jiangjialiang Middle Neolithic assemblage, the advanced attrition frequency was higher in males in both age categories (young males 8.1%, young females 2.6%, old males 7.1%, old females 2.9%, $P = 0.002$, 0.012 respectively, Table 9). The advanced attrition frequency of the Jiangjialiang young males was especially high in the anterior teeth (12.8%, Table 9, Figure 6).

Discussion

Sex differences in the frequencies of caries and dental attrition

In the Tuchengzi Warring States assemblage, young females had a caries frequency over four times that of young males (Figure 4). For advanced attrition, in the Jiangjialiang Middle Neolithic assemblage, males had a frequency about

Table 4. Caries prevalence for age, sex and group

	Jiangjialiang				Tuchengzi				Lamadong				Group differences		
	A	O	%	Sex	A	O	%	Sex	A	O	%	Sex	JJL-TCZ	JJL-LMD	TCZ-LMD
Young male															
Ant	2	172	1.2	0.734	1	100	1.0	0.733	7	201	3.5	0.482	0.633	0.264	0.378
Pre	0	141	0.0	—	1	101	1.0	0.262	15	186	8.1	0.590	0.867	0.001	0.026
Mol	7	183	3.8	0.890	4	140	2.9	0.003	44	277	15.9	0.128	0.868	0.000	0.000
Total	9	496	1.8	0.944	6	341	1.8	0.000	66	664	9.9	0.162	0.837	0.000	0.000
Young female															
Ant	0	99	0.0	—	4	168	2.4	—	27	535	5.0	—	0.305	0.044	0.210
Pre	0	91	0.0	—	8	195	4.1	—	45	459	9.8	—	0.115	0.004	0.022
Mol	5	119	4.2	—	36	294	12.2	—	118	575	20.5	—	0.022	0.000	0.003
Total	5	309	1.6	—	48	657	7.3	—	190	1569	12.1	—	0.001	0.000	0.001
Old male															
Ant	0	117	0.0	—	20	218	9.2	0.711	16	314	5.1	0.859	0.002	0.028	0.096
Pre	2	107	1.9	0.454	25	228	11.0	0.906	51	320	15.9	0.630	0.008	0.001	0.125
Mol	11	140	7.9	0.898	60	311	19.3	0.364	96	398	24.1	0.330	0.003	0.000	0.148
Total	13	364	3.6	0.941	105	757	13.9	0.386	163	1032	15.8	0.490	0.000	0.000	0.289
Old female															
Ant	0	109	0.0	—	18	166	10.8	—	9	174	5.2	—	0.001	0.039	0.083
Pre	0	113	0.0	—	18	162	11.1	—	28	154	18.2	—	0.001	0.000	0.105
Mol	13	160	8.1	—	50	218	22.9	—	51	180	28.3	—	0.000	0.000	0.265
Total	13	382	3.4	—	86	546	15.8	—	88	508	17.3	—	0.000	0.000	0.546
Total															
Ant	2	497	0.4	—	43	652	6.6	—	59	1224	4.8	—	0.000	0.000	0.132
Pre	2	452	0.4	—	52	686	7.6	—	139	1119	12.4	—	0.000	0.000	0.002
Mol	36	602	6.0	—	150	963	15.6	—	309	1430	21.6	—	0.000	0.000	0.000
Total	40	1551	2.6	—	245	2301	10.6	—	507	3773	13.4	—	0.000	0.000	0.002

Abbreviations: Ant, incisors and canines; Pre, premolars; Mol, molars; A, the number of affected teeth; O, the number of observed teeth; %, A/O $\times 100$; JJL, Jiangjialiang; TCZ, Tuchengzi; LMD, Lamadong. Significance is set at $P < 0.05$ for sex difference and $P < 0.017$ for group difference (Bonferroni correction); significant probabilities are in bold face.

Table 5. Antemortem tooth loss prevalence for age, sex and group

	Jiangjialiang				Tuchengzi				Lamadong				Group differences		
	A	O	%	Sex	A	O	%	Sex	A	O	%	Sex	JJL-TCZ	JJL-LMD	TCZ-LMD
Young male															
Ant	0	232	0.0	0.012	0	176	0.0	0.113	12	424	2.8	0.842	—	0.023	0.053
Pre	1	160	0.6	0.096	2	114	1.8	0.699	9	282	3.2	0.408	0.767	0.158	0.653
Mol	3	210	1.4	0.011	1	160	0.6	0.043	24	362	6.6	0.107	0.816	0.009	0.006
Total	4	602	0.7	0.000	3	450	0.7	0.025	45	1068	4.2	0.140	0.705	0.000	0.001
Young female															
Ant	6	163	3.7		9	422	2.1		24	969	2.5		0.441	0.534	0.845
Pre	5	115	4.3		2	282	0.7		30	648	4.6		0.038	0.913	0.005
Mol	11	153	7.2		17	377	4.5		79	814	9.7		0.300	0.406	0.003
Total	22	431	5.1		28	1081	2.6		133	2431	5.5		0.021	0.846	0.000
Old male															
Ant	22	218	10.1	0.048	23	431	5.3	0.302	66	792	8.3	0.129	0.037	0.497	0.070
Pre	9	148	6.1	0.441	10	290	3.4	0.038	54	527	10.2	0.010	0.302	0.168	0.001
Mol	19	201	9.5	0.333	29	395	7.3	0.104	140	665	21.1	0.139	0.462	0.000	0.000
Total	50	567	8.8	0.014	62	1116	5.6	0.005	260	1984	13.1	0.003	0.015	0.007	0.000
Old female															
Ant	11	231	4.8		25	337	7.4		45	401	11.2		0.271	0.009	0.103
Pre	6	167	3.6		18	224	8.0		45	266	16.9		0.110	0.000	0.005
Mol	14	218	6.4		33	294	11.2		77	301	25.6		0.088	0.000	0.000
Total	31	616	5.0		76	855	8.9		167	968	17.3		0.007	0.000	0.000
Total															
Ant	39	844	4.6		57	1366	4.2		147	2586	5.7		0.693	0.273	0.049
Pre	21	590	3.6		32	910	3.5		138	1723	8.0		0.921	0.000	0.000
Mol	47	782	6.0		80	1226	6.5		320	2142	14.9		0.713	0.000	0.000
Total	107	2216	4.8		169	3502	4.8		605	6451	9.4		0.953	0.000	0.000

Table 6. Periapical abscess prevalence for age, sex and group

	Jiangjialiang				Tuchengzi				Lamadong				Group differences		
	A	O	%	Sex	A	O	%	Sex	A	O	%	Sex	JJL-TCZ	JJL-LMD	TCZ-LMD
Young male															
Ant	1	230	0.4	0.690	3	173	1.7	0.940	13	412	3.2	0.246	0.427	0.048	0.494
Pre	0	157	0.0	0.021	2	114	1.8	0.964	6	272	2.2	0.508	0.344	0.148	0.914
Mol	3	203	1.5	0.920	2	157	1.3	0.751	9	330	2.7	0.962	0.772	0.520	0.495
Total	4	590	0.7	0.101	7	444	1.6	0.448	28	1014	2.8	0.940	0.277	0.007	0.240
Young female															
Ant	2	146	1.4		5	403	1.2		18	925	1.9		0.756	0.882	0.498
Pre	5	104	4.8		3	278	1.1		20	608	3.3		0.062	0.625	0.091
Mol	1	135	0.7		2	362	0.6		21	699	3.0		0.682	0.227	0.017
Total	8	385	2.1		10	1043	1.0		59	2232	2.6		0.157	0.636	0.003
Old male															
Ant	6	178	3.4	0.998	7	406	1.7	0.965	31	727	4.3	0.049	0.349	0.743	0.035
Pre	2	132	1.5	0.741	13	280	4.6	0.183	25	471	5.3	0.886	0.194	0.104	0.818
Mol	2	170	1.2	0.707	11	363	3.0	0.740	20	519	3.9	0.588	0.321	0.141	0.640
Total	10	480	2.1	0.903	31	1049	3.0	0.758	76	1717	4.4	0.214	0.419	0.027	0.065
Old female															
Ant	6	210	2.9		6	305	2.0		26	355	7.3		0.718	0.042	0.003
Pre	2	157	1.3		4	204	2.0		13	220	5.9		0.928	0.045	0.068
Mol	2	193	1.0		10	260	3.8		6	220	2.7		0.122	0.376	0.671
Total	10	560	1.8		20	769	2.6		45	795	5.7		0.423	0.001	0.004
Total															
Ant	15	764	2.0		21	1287	1.6		88	2419	3.6		0.705	0.031	0.001
Pre	9	550	1.6		22	876	2.5		64	1571	4.1		0.359	0.010	0.058
Mol	8	701	1.1		25	1142	2.2		56	1768	3.2		0.143	0.007	0.147
Total	32	2015	1.6		68	3305	2.1		208	5758	3.6		0.263	0.000	0.000

3-fold that of females in both age categories (Figure 5).

It is widely reported that females generally display poorer dental health than males in past and present contexts, espe-

cially in the prevalence of caries (Walker and Erlandson, 1986; Walker and Hewlett, 1990; Larsen, 1997; Lukacs and Thompson, 2008). One factor contributing to this difference

Table 7. Alveolar resorption prevalence for age, sex and group

Jiangjialiang					Tuchengzi				Lamadong				Group differences		
A	O	%	Sex		A	O	%	Sex	A	O	%	Sex	JJL-TCZ	JJL-LMD	TCZ-LMD
Young male															
Ant	0	230	0.0	0.045	0	173	0.0	0.876	1	412	0.2	0.459	—	0.767	0.654
Pre	5	157	3.2	0.056	0	114	0.0	0.197	6	272	2.2	0.889	0.143	0.764	0.251
Mol	25	203	12.3	0.418	7	157	4.5	0.331	30	330	9.1	0.880	0.016	0.298	0.105
Total	30	590	5.1	0.340	7	444	1.6	0.085	37	1014	3.6	0.998	0.005	0.209	0.050
Young female															
Ant	4	146	2.7		2	403	0.5		7	925	0.8		0.077	0.077	0.866
Pre	10	104	9.6		7	278	2.5		16	608	2.6		0.007	0.001	0.897
Mol	12	135	8.9		26	362	7.2		60	699	8.6		0.655	0.959	0.500
Total	26	385	6.8		35	1043	3.4		83	2232	3.7		0.008	0.009	0.676
Old male															
Ant	2	178	1.1	0.835	4	406	1.0	0.703	18	727	2.5	0.898	0.770	0.415	0.129
Pre	5	132	3.8	0.623	10	280	3.6	0.966	23	471	4.9	0.124	0.863	0.768	0.507
Mol	44	170	25.9	0.998	66	363	18.2	0.230	115	519	22.2	0.457	0.053	0.371	0.176
Total	51	480	10.6	0.755	80	1049	7.6	0.295	156	1717	9.1	0.316	0.065	0.351	0.207
Old female															
Ant	4	210	1.9		3	305	1.0		10	355	2.8		0.617	0.694	0.159
Pre	9	157	5.7		8	204	3.9		18	220	8.2		0.579	0.480	0.104
Mol	51	193	26.4		37	260	14.2		55	220	25.0		0.002	0.828	0.004
Total	64	560	11.4		48	769	6.2		83	795	10.4		0.001	0.626	0.004
Total															
Ant	10	764	1.3		9	1287	0.7		36	2419	1.5		0.248	0.851	0.054
Pre	29	550	5.3		25	876	2.9		63	1571	4.0		0.029	0.259	0.174
Mol	132	701	18.8		136	1142	11.9		260	1768	14.7		0.000	0.014	0.036
Total	171	2015	8.5		170	3305	5.1		359	5758	6.2		0.000	0.001	0.037

Table 8. Calculus prevalence for age, sex and group

Jiangjialiang					Tuchengzi				Lamadong				Group differences		
A	O	%	Sex		A	O	%	Sex	A	O	%	Sex	JJL-TCZ	JJL-LMD	TCZ-LMD
Young male															
Ant	50	167	29.9	0.051	49	99	49.5	0.706	150	199	75.4	0.001	0.002	0.000	0.000
Pre	41	135	30.4	0.067	55	100	55.0	0.008	134	184	72.8	0.127	0.000	0.000	0.004
Mol	95	177	53.7	0.786	72	136	52.9	0.298	182	270	67.4	0.711	0.989	0.005	0.006
Total	186	479	38.8	0.014	176	335	52.5	0.052	466	653	71.4	0.003	0.000	0.000	0.000
Young female															
Ant	39	91	42.9		88	167	52.7		330	529	62.4		0.168	0.001	0.033
Pre	33	75	44.0		72	190	37.9		300	453	66.2		0.438	0.000	0.000
Mol	60	107	56.1		131	279	47.0		370	562	65.8		0.136	0.069	0.000
Total	132	273	48.4		291	636	45.8		1000	1544	64.8		0.518	0.000	0.000
Old male															
Ant	29	101	28.7	0.580	137	221	62.0	0.006	221	303	72.9	0.485	0.000	0.000	0.010
Pre	33	96	34.4	0.849	128	225	56.9	0.544	237	303	78.2	0.549	0.000	0.000	0.000
Mol	61	130	46.9	0.835	215	307	70.0	0.042	315	383	82.2	0.563	0.000	0.000	0.000
Total	123	327	37.6	0.694	480	753	63.7	0.001	773	989	78.2	0.728	0.000	0.000	0.000
Old female															
Ant	33	99	33.3		77	163	47.2		129	169	76.3		0.037	0.000	0.000
Pre	41	112	36.6		83	156	53.2		109	145	75.2		0.010	0.000	0.000
Mol	72	160	45.0		132	216	61.1		138	173	79.8		0.003	0.000	0.000
Total	146	371	39.4		292	535	54.6		376	487	77.2		0.000	0.000	0.000
Total															
Ant	151	458	33.0		351	650	54.0		830	1200	69.2		0.000	0.000	0.000
Pre	148	418	35.4		338	671	50.4		780	1085	71.9		0.000	0.000	0.000
Mol	288	574	50.2		550	938	58.6		1005	1388	72.4		0.002	0.000	0.000
Total	587	1450	40.5		1239	2259	54.8		2615	3673	71.2		0.000	0.000	0.000

could be ascribed to female life history connected with reproductive physiology: cariogenic oral environments could be produced by changes in saliva composition and volume,

which is accompanied with changes in estrogen levels triggered by menstruation and pregnancy (Lukacs and Largaespada, 2006; Lukacs and Thompson, 2008). How-

Table 9. Advanced attrition prevalence for age, sex and group

	Jiangjialiang				Tuchengzi				Lamadong				Group differences		
	A	O	%	Sex	A	O	%	Sex	A	O	%	Sex	JJL-TCZ	JJL-LMD	TCZ-LMD
Young male															
Ant	22	172	12.8	0.032	2	100	2.0	0.269	6	201	3.0	0.620	0.005	0.001	0.904
Pre	9	141	6.4	0.726	0	101	0.0	0.128	4	186	2.2	0.920	0.025	0.098	0.339
Mol	9	183	4.9	0.035	2	140	1.4	0.822	6	277	2.2	0.585	0.160	0.174	0.888
Total	40	496	8.1	0.002	4	341	1.2	0.973	16	664	2.4	0.895	0.000	0.000	0.276
Young female															
Ant	4	99	4.0		0	168	0.0		22	535	4.1		0.035	0.808	0.016
Pre	4	91	4.4		7	195	3.6		11	459	2.4		1.000	0.473	0.554
Mol	0	119	0.0		2	294	0.7		8	575	1.4		0.905	0.411	0.553
Total	8	309	2.6		9	657	1.4		41	1569	2.6		0.279	0.864	0.099
Old male															
Ant	6	117	5.1	0.834	8	218	3.7	0.186	16	314	5.1	0.388	0.727	0.816	0.571
Pre	9	107	8.4	0.114	13	228	5.7	0.981	26	320	8.1	0.681	0.486	0.912	0.358
Mol	11	140	7.9	0.063	21	311	6.8	0.274	19	398	4.8	0.462	0.822	0.249	0.333
Total	26	364	7.1	0.012	42	757	5.5	0.983	61	1032	5.9	0.176	0.361	0.478	0.824
Old female															
Ant	4	109	3.7		12	166	7.2		13	174	7.5		0.332	0.293	0.903
Pre	3	113	2.7		10	162	6.2		15	154	9.7		0.288	0.042	0.334
Mol	4	160	2.5		9	218	4.1		12	180	6.7		0.567	0.120	0.367
Total	11	382	2.9		31	546	5.7		40	508	7.9		0.063	0.003	0.194
Total															
Ant	36	497	7.2		22	652	3.4		57	1224	4.7		0.005	0.042	0.232
Pre	25	452	5.5		30	686	4.4		56	1119	5.0		0.453	0.763	0.619
Mol	24	602	4.0		34	963	3.5		45	1430	3.1		0.744	0.412	0.690
Total	85	1551	5.5		86	2301	3.7		158	3773	4.2		0.013	0.048	0.424

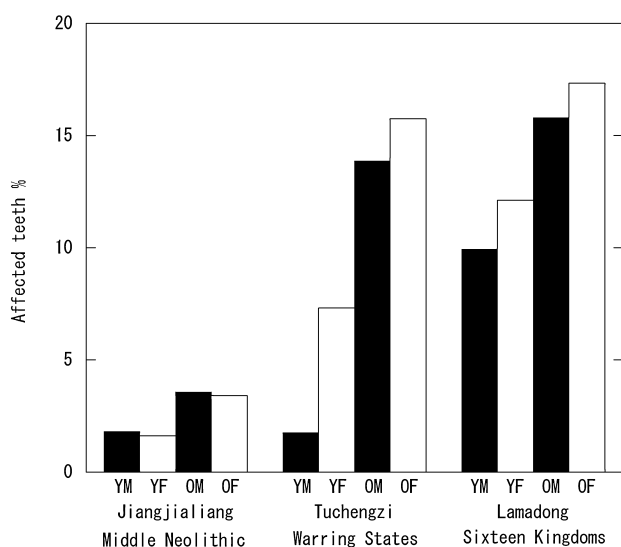


Figure 4. Percentage differences in dental caries between males and females. Abbreviations: YM, young males; YF, young females; OM, old males; OF, old females.

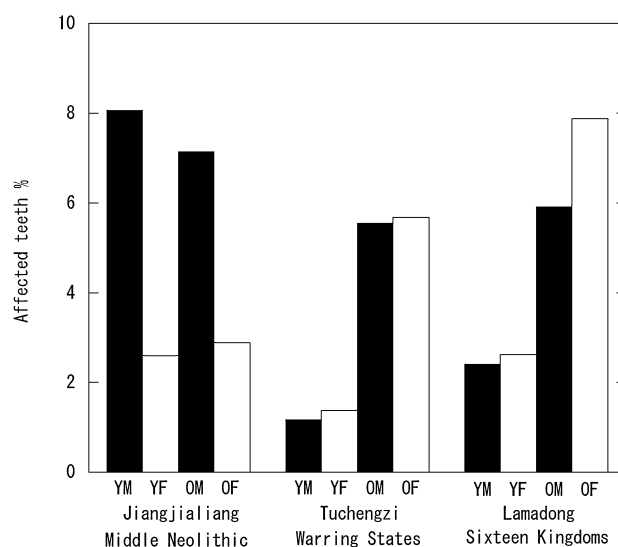


Figure 5. Percentage differences in advanced attrition between males and females.

ever, the sex difference in caries prevalence among the Tuchengzi Warring States assemblage is considerably larger compared to other Asian groups in past societies reported by Lukacs and Thompson (2008) (male average 8.1%, female average 10.9%). Therefore, non-biological factors should also be considered as causes for the sex differences in the prevalence of caries among the Tuchengzi Warring States assemblage.

Previous studies suggest two cultural factors related to the sexual division of labor contributing to sex difference in caries prevalence (Larsen, 1997; Walker and Hewlett, 1990). Firstly, females tend to consume a greater proportion of carbohydrate-rich foods, which are thought to be more cariogenic, while males tend to consume a greater proportion of meat products, which are less cariogenic. Secondly, females more frequently access foods during food procurement and

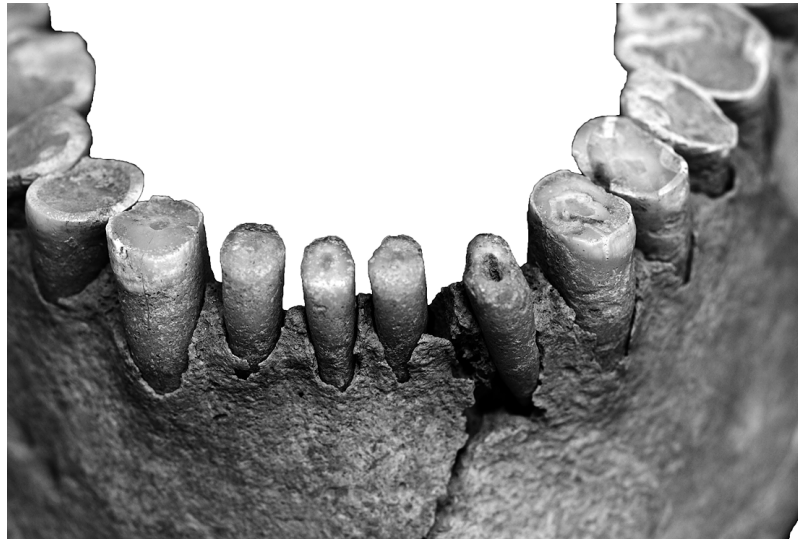


Figure 6. An example of advanced attrition (including pulp exposure) of the anterior teeth in an adult male (M27) from the Jiangjialiang site, Middle Neolithic Period.

production.

According to the House of Jin *Shiji* (Records of the Grand Historian), the Tuchengzi fortress was the stronghold for the Xianyun or Beidi groups (nomadic peoples) during the Spring and Autumn period, but fell under the jurisdiction of the Zhao state during the Warring States period. The existence of weapons embedded in and/or interred with the burial individuals, as well as the historical documentation, suggests that males of the Tuchengzi Warring States originated from a large number of frontier guards and/or pioneers (*Tuntianbing*) of the Zhao state (Gu, 2007). In 307 BC, King Wuling (325–299 BC) of the Zhao state pushed the military reformation called *Hufuqishe* (barbarian clothing and mounted archers), which adopted the horseback riding styles of nomads (Di Cosmo, 2002). Judging from a historical record (*Shiji*), when King Wuling organized the cavalry on the frontier, he relied heavily on local recruits, people who had lived in the northern frontier for a long time and were acquainted with nomads, and who had traded and/or had conflict with them, since these experiences could be advantageous for military tasks (Di Cosmo, 2002: 137–138). Such an opportunity to access animal products might have inhibited the caries prevalence in young males of the Tuchengzi Warring States. It is likely that there was a different living environment for each sex because of military service, which accounts for lower caries prevalence in young males of this site, although there is little concrete evidence to support this hypothesis.

What factors can explain the higher prevalence of dental attrition in males than females at the Jiangjialiang site? This sex difference was larger in the anterior teeth component in the young age cohort (Table 9, Figure 6). In the anterior teeth component in the old age cohort, the AMTL prevalence of males was significantly higher than that of females, instead of advanced attrition (Table 5). This age-related shift in sex difference pattern from advanced attrition to AMTL in the anterior teeth component might mean that severe attrition finally led to AMTL in the anterior teeth of males in this

site. It is likely that some of the sexual divisions in labor, such as the preparation of plant fibers or animal sinew using teeth (Ubelaker et al., 1969; Lukacs and Pastor, 1988; Brown and Molnar, 1990), induced the sex differences in advanced attrition and AMTL prevalence, since the grave goods were different between males and females in this site (Hebei Provincial Institute of Cultural Relics, 2001). Previous studies show a sex difference in the frequency of activity-induced dental abrasion (Lukacs and Pastor, 1988; Brown and Molnar, 1990). Detailed investigation on worn teeth is needed to reveal what activity induced the observed sex difference in advanced attrition prevalence at this site.

Changes in oral disease over time

The results of this study demonstrated that the caries prevalence steadily increased over time (Figure 2). The increase of the AMTL prevalence over time was slightly irregular, even though over 7% AMTL prevalence was found only in the post Spring/Autumn period assemblages, except for the Zhukaigou Late Neolithic/Early Dynasty assemblage (Figure 2). The changes in periapical abscess and calculus prevalence mostly agreed with that of the caries prevalence (Figure 3). In contrast, the advanced attrition prevalence decreased over time. The alveolar resorption prevalence did not show any constant change (Figure 3). Notably, for some of the sites included in this comparison (e.g. Miaoziyou), only a limited number of individuals were available. The results for those sites, however, are mostly in line with the tendency shown by the larger assemblages. Indeed, even though the sample size was rather limited in the Miaoziyou Middle Neolithic assemblage, caries and AMTL prevalence of this assemblage were similar to that of the Jiangjialiang Middle Neolithic assemblage, which is geographically and temporally very close to the former (Table 3, Figure 1, Figure 2). Therefore, the results of the Miaoziyou Middle Neolithic assemblage could be provisionally used as supplemental data here.

Some of the present results agree with previous studies

dealing with the same sample, and the outcome of the Lamadong Sixteen Kingdoms assemblage does not contradict previous bioarchaeological studies (Zhang, 2003; Eng, 2007). Eng (2007) reported a higher frequency of individuals with caries and AMTL among the Lamadong Sixteen Kingdoms assemblage than surrounding agricultural groups of different periods. Further, the caries prevalence of the Tuchengzi Warring States assemblage as shown in this study roughly approximates to that reported by Gao et al. (2006).

The gradual increase in oral disease (except alveolar resorption) and the decrease in advanced attrition as shown in this study mostly agree with the hypothesis established on the basis of previous works. The reason underlying the high alveolar resorption prevalence of the Jiangjialiang Middle Neolithic assemblage is unclear. It is possible that continuous eruption was wrongly diagnosed as alveolar resorption even though the first author carefully checked whether there was active bone formation or periodontal pockets on the alveolar crest.

Less than 3% of the caries prevalence of both Middle Neolithic assemblages could be considered congruent with the subsistence pursued based on archaeological evidence. Several joint projects between paleoclimatologists and archaeologists suggest that the natural and social environments in the Great Wall Region were greatly influenced by climatic change at the beginning of the third millennium BC (Tian and Shi, 1991; Miyamoto, 2000, 2005; Jin, 2004). The warm and wet climate of the Hypsithermal interval between the Early Neolithic and Middle Neolithic periods may have expedited the domestication of foxtail millet (*Setaria italic*) and broomcorn millet (*Panicum miliaceum*) in the Central Plains and a mixed economy between hunting-gathering and millet agriculture developed in the Great Wall Region. In the Miaozigou site, where rich archaeological information was available, analysis of the production tools suggested a mixed economy between primitive agriculture and hunting-gathering, as well as possible animal herding (Inner Mongolia Institute of Cultural Relics and Archeology, 2003). On the contrary, the Jiangjialiang site provided relatively limited archaeological information, but taking account of the geographically and temporally close distance between the sites, their subsistence patterns seem similar.

Approximately 6–7% of the caries prevalence of the both Late Neolithic/Early Dynasty assemblages also does not contradict the archaeologically reconstructed pattern of subsistence. From about 3000–2000 BC, when a decrease in environmental resources accompanied a gradual decline in the warm and wet climate, domestic herd animals became a staple subsistence resource, and variations in types of subsistence increased among animal herding, millet agriculture, and hunting-gathering in the Great Wall Region (Chang, 1977; Miyamoto, 2000, 2005; Di Cosmo, 2002; Jin, 2004; Honeychurch and Amartuvshin, 2006). The results of zooarchaeological studies show that in the Central Plains, the ratio of the number of deer to other mammals was constantly high, while that of pigs increased during the cooling interval beginning in the third millennium BC. Meanwhile, in the Great Wall Region, the percentage of herd animal remains (e.g. sheep and cattle) recovered from archaeological sites consistently increased through time, while remains of deer

decreased during this time (Miyamoto, 2000: 61–73; Miyamoto 2005: 209–219). This contrasting pattern between the two regions suggests different patterns of mixed subsistence economies: millet farming and pig domestication with some hunting and gathering was predominant in the Central Plains, while millet farming and sheep/cattle herding developed in the Great Wall Region. Pastoral nomadism and increased dependence on animal herding began to emerge during the second millennium BC in the Great Wall Region (Miyamoto, 2000, 2005). The grave goods unearthed from the Dadianzi site are characterized by the Lower Xiajiadian culture, where the economy was millet farming supplemented with animal husbandry and hunting (Institute of Archaeology, Chinese Academy of Social Sciences, 1996).

In the Zhukaigou site, the degree of dependence on animal husbandry was slightly more significant than in the Dadianzi site (Archaeological Institute of Inner Mongolia and Ordos Museum, 2000), probably because of the cooler, drier climate there (Kong et al., 1991). The subsistence with regard to consumed agricultural foods was mostly common between the eastern (south-central Inner Mongolia) and western part (western Liaoning) of the Great Wall Region (Miyamoto, 2000: 32–45). Excavated microliths, vessels, and bronze weapons suggest that there was much more active cultural intercourse between the east and west than between the north and south, especially after the Middle Neolithic period, and both regions formed the same cultural range called the northern (Ordos) style bronze culture (Miyamoto, 2000: 32–45). However, the process of aridification and cooling was slower in western Liaoning than in south-central Inner Mongolia (Kong et al., 1991). It was not significant until the period of upper Xiajiadian culture (c. 3000–2600 BP) in western Liaoning, and it was still relatively humid and warm in the period of lower Xiajiadian culture (c. 4000–3500 BP). In south-central Inner Mongolia, the aridification and cooling trends were already remarkable in the Zhukaigou cultural period, which was mostly simultaneous with the lower Xiajiadian culture (Kong et al., 1991).

In brief, the increase in caries prevalence from the Middle Neolithic to the Late Neolithic/Early Dynasty period could have been caused by the transition of subsistence from a mixed economy of primitive farming and hunting-gathering to a mixed economy of more intensive farming and animal husbandry/hunting.

The finding that over 10% of the caries prevalence occurred in post-Spring/Autumn period assemblages also agrees with this explanation based on historical documents and stable isotope analyses. Historical documents suggest an increase in the productivity of millet agriculture was prompted by the widespread use of iron agricultural tools and new farming techniques well adapted to the windy and dry environment of the Great Wall Region. Advances in agricultural technologies and theories led to an increase of farming productivity in the Great Wall Region between the Han dynasty (206 BC–220 AD) and Sixteen Kingdoms period (Liu, 2001). Although iron farming instruments and the ox plow method had already emerged during the Warring States period in the Central Plains (Chang, 1977), the improvement and spread of both technologies greatly increased

during the following Han dynasty period (Liu, 2001). According to Chinese historical documents (*Qimingyaoshu*), both technologies allowed agriculturalists to perform a method of irrigation farming (*Daitianfa*) in the Great Wall Region, which was well adapted to the drought-stricken environment there (Liu, 2001). Accordingly, agricultural productivity significantly increased during this period, even in a light rainfall environment in the Great Wall Region. A stable isotope analysis of 20 individuals from the Lamadong Sixteen Kingdoms assemblage conducted by Dong et al. (2007) suggests a very high ratio of vegetable food out of the whole diet consumed ($\delta^{15}\text{N} = 6.42\text{‰}$, $\delta^{13}\text{C} = -9.67\text{‰}$). The ratio of C4 plants out of the total amount of vegetable foods consumed was 84.5%, which, according to a historical document called *Weishu*, should refer to millet. Furthermore, it is highly possible that diets became more refined between the Warring States and the Sixteen Kingdoms periods because threshing and polishing of grains became more efficient due to the popularization of the pedal mortar (Liu, 2001; Luo, 2001).

The introduction of wheat farming may also have contributed to the high frequency of dental caries during the Spring and Autumn/Warring States period. Wheat needs to be milled to produce gluten, while millet can be directly consumed as gruel immediately after threshing. In this sense, wheat could be more cariogenic than millet. Wheat remains have been unearthed from sites dating from the Longshan period (Crawford, 2006), and historical documents indicate that wheat had already replaced millet as the principle grain by the Han dynasty period in the Central Plains (Gu, 2007). In the Great Wall Region, however, historical documents and stable isotope analyses on human skeletal samples indicate that millet was still the main dietary staple until at least the Sixteen Kingdoms period (Dong et al., 2007). A stable isotope analysis of 17 individuals from the Tuchengzi Warring States assemblage conducted by Gu (2007) suggests the relatively high ratio of vegetable food out of the whole diet consumed ($\delta^{15}\text{N} = 7.69\text{‰}$, $\delta^{13}\text{C} = -9.94\text{‰}$). Of all vegetables, the C4 and C3 plants consumed were at a ratio of 77% : 23%, respectively. Considering the farming products described in historical documents, the former is expected to be millet, and the latter wheat (Gu, 2007).

In summary, the outcomes of this study suggest that consumption of more carbohydrate-rich and/or refined foods resulted in poorer oral health in the contact zone between nomadic peoples and Chinese states. However, only millet agricultural groups were selected as samples in this study, regardless of differences in the degree of dependence on agricultural foods among the groups. This could explain the deterioration of oral health through time for agricultural groups (including semi-agricultural and semi-pastoral society) but not for the groups that mainly depended on animal herding. Zhang et al. (2009) found a very low caries prevalence (3.3%) in a nomad sample during the Spring and Autumn/Warring States period (at the Xindianzi site, which is about 50 km from the Yinniugou site). Here, the oral condition seems to have diversified because of the coexistence of agriculturalists and nomads during the Spring and Autumn/Warring States period in this contact zone.

Regarding a concern on the cohesiveness of the samples

of this study, the skeletal assemblages considered here are not only biologically but also culturally heterogeneous since population movements had frequently occurred in the Great Wall Region (Zhu, 2002). Although these assemblages are currently the best alternative for studying prehistoric/historic agricultural groups in this region, the differences of some cultural practices and political influences among these assemblages might have influenced the outcomes of this study (e.g. Buddhism, one of the precepts of which is vegetarianism, began permeating throughout the Chinese society during the Sixteen Kingdoms period) (Misaki, 2002: 164–171). Further bioarchaeological studies using newly excavated samples are needed to ascertain whether the pattern of oral health change revealed by this study was universal to other samples in the Great Wall Region.

Acknowledgments

K.O. would like to thank Ekaterina Pechenkina (The Queens College of the City University of New York) and Daniel Temple (University of North Carolina) for advice regarding paleopathological techniques and English expressions, and Kazuo Miyamoto (Kyushu University) for advice regarding the archaeology of China. The authors are grateful to their colleagues at the Research Center for Chinese Frontier Archaeology of Jilin University for assistance with the skeletal samples.

Grant sponsorships: Japan Society for the Promotion of Science, Postdoctoral Fellowships for Research Abroad.

References

- Archaeological Institute of Inner Mongolia and Ordos Museum (2000) Zhukaigou—Excavation Report on the Early Bronze Age Site. Cultural Relics Publishing House, Beijing (in Chinese with English summary).
- Brothwell D.R. (1981) Digging Up Bones. Cornell University Press, Ithaca, NY.
- Brown T. and Molnar S. (1990) Interproximal grooving and task activity in Australia. *American Journal of Physical Anthropology*, 81: 545–553.
- Buikstra J.E. and Ubelaker D.H. (1994) Standards for Data Collection from Human Skeletal Remains. *Arkansas Archaeological Survey*, Fayetteville.
- Cai L. and Qiu S. (1984) Carbon-13 evidence for ancient diets in China. *Kaogu*, 10: 949 (in Chinese).
- Chang K. (1977) The Archaeology of Ancient China. [trans. Hakari H. (1980) Yuzankaku, Tokyo (in Japanese).]
- Chen S. (2009) A Research on the Human Skeletons of Sanyan Culture from Lamadong Graveyard. Ph.D. dissertation, Jilin University (in Chinese with English summary).
- Crawford G.W. (2006) East Asian Plant Domestication. In: Stark M.T. (ed.), *Archaeology of Asia*. Blackwell Publishing, Malden, pp. 77–95.
- Dias G. and Tayles N. (1997) ‘Abscess cavity’—a misnomer. *International Journal of Osteoarchaeology*, 7: 548–554.
- Di Cosmo N. (2002) *Ancient China and Its Enemies: The Rise of Nomadic Power in East Asian History*. Cambridge University Press, Cambridge.
- Dong Y., Hu Y., Zhang Q., Cui Y., Guan L., Wang C., and Wan X. (2007) Stable isotopic analysis on human bones of the Lamadong site, Beipiao, Liaoning province. *Acta Anthropologica Sinica*, 26: 77–84 (in Chinese with English summary).
- Douglas M.T. (2006) Subsistence change and dental health in the people of Non Nok Tha, northeast Thailand. In: Oxenham M.

- and Tayles N. (eds.), *Bioarchaeology of Southeast Asia*. Cambridge University Press, Cambridge, pp. 191–219.
- Eng J.T. (2007) *Nomadic Pastoralists and the Chinese Empire: A Bioarchaeological Study of China's Northern Frontier*. Ph.D. dissertation, University of California.
- Gao Y., Zhang Q., and Zhu H. (2006) Distribution of dental caries of ancient population from Inner-Mongolia and Helinge'er Tuchengzi Site. *Journal of Jilin University*, 32: 515–516 (in Chinese).
- Gu Y. (2007) *A research on the skeletons of the Warring-States period from Tuchengzi site, Helinge'er county, Inner Mongolian province*. Ph.D. dissertation, Jilin University (in Chinese with English summary).
- Hebei Provincial Institute of Cultural Relics (2001) The excavation at the Neolithic Jiangjialiang site, Yangyuan, Hebei. *Kaogu*, (2): 113–127 (in Chinese with English summary).
- Hillson S.W. (1996) *Dental Anthropology*. Cambridge University Press, Cambridge.
- Hillson S.W. (2001) Recording dental caries in archaeological human remains. *International Journal of Osteoarchaeology*, 11: 249–289.
- Honeychurch W. and Amartuvshin C. (2006) States on horseback: the rise of inner Asian confederations and empires. In: Stark M.T. (ed.), *Archaeology of Asia*. Blackwell Publishing, Malden, pp. 255–278.
- Huang Y. (1996) Identifications and study on the animal bones from the Zhukaigou site, Inner Mongolia. *Acta Archaeologica Sinica*, 4: 515–536 (in Chinese with English summary).
- Inner Mongolia Institute of Cultural Relics and Archeology (2003) Miaoziyou and Dabagou: The Report on Excavation of Ancient Sites of Primitive Inhabitant Tribes in the New Stone Age. *Encyclopedia of China Publishing House*, Beijing (in Chinese with English summary).
- Inner Mongolia Institute of Cultural Relics and Archeology (2006) The summary of the excavation at the Tuchengzi site, Helinge'er county. *Inner Mongolian Cultural Relics and Archaeology*, (1): 9–16 (in Chinese).
- Inner Mongolia Institute of Cultural Relics and Archeology and Japan Kyoto Society of Chinese Archaeology (2001) The report for the excavation of the Yinniugou site in 1997. In: Tian G. and Akiyama S. (eds.), *The Archaeology in the Daihai Region-2*. Kexue, Beijing, pp. 278–327 (in Chinese).
- Inoue N., Pan Q., Sakashita R., and Kamegai T. (1997) Tooth and Facial Morphology of Ancient Chinese Skulls: Report of Anthropological and Dental Pathological Study. *Therapeia Publishing Co.*, Tokyo.
- Institute of Archaeology, Chinese Academy of Social Sciences (1996) *The Dadianzi Site—The Site of the Lower Xiajadian Culture and the Excavation Report on the Cemetery*. Kexue, Beijing (in Chinese with English summary).
- Jin G. (2004) Climate and environmental changes of the mid-Holocene epoch in north China. *Acta Archaeologica Sinica*, 4: 485–505 (in Chinese with English summary).
- Kaifu Y., Kasai K., Townsend G.C., and Richards L.C. (2003) Tooth wear and the “design” of the human dentition: a perspective from evolutionary medicine. *American Journal of Physical Anthropology*, 122: 47–61.
- Kong Z., Du N., Liu G., and Yang H. (1991) Preliminary environmental archaeology research on the period between 8000–2400 BP in Chifeng, the Inner Mongolia Autonomous Region. In: Zhou K. (ed.), *Environmental Archaeology Research*. Kexue, Beijing, pp. 112–119 (in Chinese).
- Larsen C.S. (1997) *Bioarchaeology: Interpreting Behavior from the Human Skeleton*. Cambridge University Press, Cambridge.
- Li F. (2008) *A Research on Human Skeletons of the Neolithic Age in Jiangjialiang, Yangyuan, Hebei, China*. Kexue, Beijing (in Chinese).
- Li R. and Huang J. (1991) Dental disease of the Neolithic population from Xiawanggang. *Acta Anthropologica Sinica*, 10: 200–205 (in Chinese with English summary).
- Liaoning Institute of Cultural Relics and Archeology (2004) Excavation of the Cemetery at Lamadong, Beipiao, Liaoning, in 1998. *Acta Archaeologica Sinica*, (2): 209–242 (in Chinese with English summary).
- Liu W., Zhang Q.C., Wu X.J., and Zhu H. (2010) Tooth wear and dental pathology of the Bronze–Iron Age people in Xinjiang, Northwest China: Implications for their diet and lifestyle. *Homo*, 61: 102–116.
- Liu Y. (2001) *Chinese civilization in a new light-4. Qin and Han dynasties*. [trans. Ito S. (2005) Sougensha, Osaka (in Japanese).]
- Lovejoy C.O., Meindl R.S., Pryzbeck T.R., and Mensforth R.P. (1985) Chronological metamorphosis of the auricular surface of the ilium: a new method for the determination of adult skeletal age at death. *American Journal of Physical Anthropology*, 68: 15–28.
- Lukacs J.R. (1989) Dental paleopathology: methods for reconstructing dietary patterns. In: Iscan M.Y. and Kennedy K.A.R. (eds.), *Reconstruction of Life from the Skeleton*. Alan R. Liss, New York, pp. 261–286.
- Lukacs J.R. and Largaespada L. (2006) Explaining sex differences in dental caries rates: saliva, hormones and “life history” etiologies. *American Journal of Human Biology*, 18: 540–555.
- Lukacs J.R. and Pastor R.F. (1988) Activity-induced patterns of dental abrasion in prehistoric Palistan: evidence from Mehrgarh and Harappa. *American Journal of Physical Anthropology*, 76: 377–398.
- Lukacs J.R. and Thompson L.M. (2008) Dental caries prevalence by sex in prehistory: magnitude and meaning. In: Irish J.D. and Nelson G.C. (eds.), *Technique and Application in Dental Anthropology*. Cambridge University Press, Cambridge, pp. 136–177.
- Luo Z. (2001) *Chinese civilization in a new light-5. The Wei, Jin, and Southern and Northern Dynasties*. [trans. Sumitani T. (2005) Sougensha, Osaka (in Japanese).]
- Mao X. and Yan Y. (1959) A research report on teeth of the Yin Dynasty Period from Anyang and Hui provinces. *Vertebrata Palasiatica*, 1: 81–85 (in Chinese).
- Meindl R.S. and Lovejoy C.O. (1985) Ectocranial suture closure: a revised method for the determination of skeletal age at death based on the lateral-anterior sutures. *American Journal of Physical Anthropology*, 68: 57–66.
- Meindl R.S., Lovejoy C.O., Mensforth R.P., and Walker R.A. (1985) A revised method of age determination using the os pubis, with a review and tests of accuracy of other current methods of pubic symphyseal aging. *American Journal of Physical Anthropology*, 68: 29–45.
- Misaki Y. (2002) *The Sixteen Kingdoms of the Five Barbarians: An Exodus in the History of China*. Tohou-shoten, Tokyo (in Japanese).
- Miyamoto K. (2000) *Archaeological Research on the Northern Border Region of Ancient China*. Chugoku-shoten, Fukuoka (in Japanese with English summary).
- Miyamoto K. (2005) *A History of China 1: From Myth to History*. Kodansha, Tokyo (in Japanese).
- Oxenham M., Cuong N.L., and Thuy N.K. (2006) The oral health consequences of the adoption and intensification of agriculture in Southeast Asia. In: Oxenham M. and Tayles N. (eds.), *Bioarchaeology of Southeast Asia*. Cambridge University Press, Cambridge, pp. 263–289.
- Oyamada J., Igawa K., Manabe Y., Kato K., Matsushita T., Rokutanda A., and Kitagawa Y. (2010) Preliminary analysis of regional differences in dental pathology of early modern commoners in Japan. *Anthropological Science*, 118: 1–8.
- Pechenkina E.A., Benfer R.A., and Wang Z. (2002) Diet and health changes at the end of the Chinese Neolithic: the Yangshao/Longshan transition in Shanxi province. *American Journal of Physical Anthropology*, 117: 15–36.

- Pechenkina E.A., Ambrose S.H., Ma X., and Benfer R.A. (2005) Reconstructing northern Chinese Neolithic subsistence practices by isotopic analysis. *Journal of Archaeological Science*, 32: 1176–1189.
- Pechenkina E.A., Benfer R.A., and Ma X. (2007) Diet and health in the Neolithic of the Wei and middle Yellow river basins, northern China. In: Cohen M.N. and Crane-Kramer G.C. (eds.), *Ancient Health: Skeletal Indicators of Agricultural and Economic Intensification*. University Press of Florida, Gainesville, pp. 255–272.
- Powell M.L. (1985) The analysis of dental wear and caries for dietary reconstruction. In: Gilbert R.I. and Mielke J.H. (eds.), *The Analysis of Prehistoric Diets*. Academic Press, Orlando, pp. 307–338.
- Sakashita R., Inoue M., Inoue N., Pan Q., and Zhu H. (1997) Dental disease in the Chinese Yin-Shang period with respect to relationships between citizens and slaves. *American Journal of Physical Anthropology*, 103: 401–408.
- Scheuler L. and Black S. (2004) *The Juvenile Skeleton*. Elsevier Academic Press, Oxford.
- StatSoft Inc. (1996) *User's manual for STATISTICA*. StatSoft Japan, Tokyo (in Japanese).
- Temple D.H. and Larsen C.S. (2007) Dental caries prevalence as evidence for agriculture and subsistence variation during the Yayoi period in prehistoric Japan: biocultural interpretations of an economy in transition. *American Journal of Physical Anthropology*, 134: 501–512.
- Tian G. and Shi P. (1991) An environmental archaeological study on primitive cultures in the southern middle Inner Mongolia. In: Inner Mongolia Institute of Cultural Relics and Archaeology (ed.), *An Anthology of Research on Primitive Cultures in Southern Middle Inner Mongolia*. Haiyang, Beijing, pp. 119–132 (in Chinese).
- Todaka Y., Oyamada J., Manabe Y., Kitagawa Y., Kato K., and Rokutanda A. (2003) The relationship between immigration and the prevalence of dental caries in the Yayoi people. *Anthropological Science*, 111: 265–292.
- Todd T.W. (1920) Age changes in the pubic bone: 1. The male white pubis. *American Journal of Physical Anthropology*, 3: 285–334.
- Turner C.G. (1979) Dental anthropological indications of agriculture among the Jomon people of central Japan: X. Peopling of the Pacific. *American Journal of Physical Anthropology*, 51: 619–636.
- Ubelaker D.H. (1989) *Human Skeletal Remains: Excavation, Analysis, Interpretation*, 2nd edn. Taraxacum, Washington, DC.
- Ubelaker D.H., Phenice T.W., and Bass W.M. (1969) Artificial interproximal grooving of the teeth in American Indians. *American Journal of Physical Anthropology*, 30: 145–150.
- Walker P.L. and Erlandson J.M. (1986) Dental evidence for prehistoric dietary change on the northern Channel Islands, California. *American Antiquity*, 51: 375–383.
- Walker P.L. and Hewlett B.S. (1990) Dental health, diet, and social status among Central African foragers and farmers. *American Anthropologist*, 92: 383–398.
- Zhang Q. (2003) Dental disease of the Three-Yan cultures from Lamadong cemetery of Beipiao. *Acta Anthropologica Sinica*, 22: 29–36 (in Chinese with English summary).
- Zhang Q., Cao J., and Zhu H. (2009) Research on dental caries of ancient populations during Bronze Age and early Iron Age in southern central Inner Mongolia. *Acta Anthropologica Sinica*, 28: 372–378 (in Chinese with English summary).
- Zhu H. (2002) The racial types of ancient population in the Inner Mongolia-Great Wall Region. *Research of China's Frontier Archaeology*, 1: 301–313 (in Chinese).