Periodontal disease in the Neolithic Jomon: inter-site comparisons of inland and coastal areas in central Honshu, Japan

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Abstract This paper examines periodontal disease as well as other oral health indicators of the Jomon population in order to understand variations in their lifestyle and their response to dietary diversity. The oral conditions of three Jomon populations in Late Jomon period are evaluated using two periodontal indicators, namely the distance measured between the cement–enamel junction to the alveolar crest (CEJ-AC distance), and the degree of inflammation of the alveolar septum. The incidence of affected individuals with moderate to severe periodontal disease ranges from 31.8% to 38.6% based on the evaluation of the CEJ-AC distance, and from 38.4% to 66.0% based on the interdental septum morphology, respectively. Comparisons of the inter-site difference (which includes that between coastal and inland populations) and sex differences were conducted with a combined dataset of the periodontal and oral health indicators (caries, antemortem tooth loss, wear, and chipping). The results indicated that inter-site and inter-sex differences are smaller in the cases with periodontal disease than in those with caries and antemortem tooth loss. In particular, almost no difference was found in the periodontal conditions between the coastal and inland sites. Although previous studies have indicated the effect of occlusal wear on the CEJ-AC distance, the results of the multivariate analysis show that the inflammation of the interdental septum is more relevant than the occlusal wear. In addition, the sex difference was significant compared to the inter-site difference, and each sex difference within a site showed a common trend. Detected inter-site and sex differences are discussed and assumed to be associated with bioarchaeological background.

Key words: periodontal disease, occlusal wear, oral health condition, Late Jomon period

Introduction

Periodontal disease is a set of inflammatory conditions affecting the tissues surrounding the teeth (gingiva, periodontal ligament, alveolar bone, and cementum) triggered by infection of periodontal bacteria (Holt and Ebersole, 2005; Hajishengallis, 2014). About 20 species of bacteria that are the major causes of periodontal disease have been identified, and these bacteria are symbiotic to the biofilm formed in the subgingival space, such as caries (Socransky and Haffajee, 2005). The bacterial group that causes periodontal disease comprises Gram-negative bacteria. However, in gingivitis and early periodontitis it has been reported that Gram-positive bacteria are more predominant than Gram-negative bacteria in plaques (Listgarten, 1976; Slots, 1979).

The onset of periodontal disease is thought to be triggered by the accumulation of dental plaque with a soft carbohydrate diet, poor oral hygiene environment, or impaired body immunity, etc. (Genco, 1996; Albandar, 2002, 2005). However, the interaction of several factors plays a significant role at the onset, and the definitive cause of periodontal disease remains unclear (Albandar, 2002; Holt and Ebersole, 2005).

Cases of oral paleopathology, including periodontal disease and dental caries, increased after the cultivation of crops began in the Neolithic period (Aufderheide et al., 1998). Furthermore, more cases have been reported since the Industrial Revolution, especially during the periods and in the areas where the refined wheat and sugar-rich food supply increased (Ismail et al., 2001). Recent DNA analysis of dental calculus has successfully recovered intraoral bacteria from ancient human bones, revealing a change in the constitution of oral bacterial in Europe from the Mesolithic to the present (Adler et al., 2013). According to this analysis, the proportion of Porphyromonas gingivitis, one of causative bacteria of periodontal disease, increased after the Neolithic, and Streptococcus mutans, which is the major bacterium of dental caries, increased rapidly over the modern period.

Pioneering studies on periodontal disease in ancient human bones have focused on the people living prior to the...
Industrial Revolution (Costa, 1982). Many previous case reports include those of the ancient Pleistocene time such as Neanderthal and Homo erectus (Trinkaus, 1985; Lozano et al., 2013; Martín-Francés et al., 2014) and those of modern times, and the prevalence rate is variable, ranging from 18% to 100% (Kerr, 1994; Oztunc et al., 2006; Lieverse et al., 2007; DeWitte and Bekvalac, 2010).

After the Neolithic period, the pruning and cultivation of plants, as well as the domestication of animals, began, and the ingestion of increasing amounts of soft carbohydrates possibly led to an increase in periodontal disease. In osteoarchaeological data, many cases of periodontal disease and antemortem tooth loss (AMTL) have been reported in groups with a high consumption of vegetable carbohydrates and cooked foods (Larsen, 1997: 80).

The presence or absence of periodontal disease in the dry bone has been evaluated based on the degree of alveolar resorption, and, in practice, the exposure of the tooth root has been measured since the 1970s (Davies et al., 1969; Lavelle and Moore, 1969; Costa, 1982). In addition, the rate of AMTL has been regarded as an indicator of periodontal disease in ancient human bones (Clarke et al., 1986; Lavigne and Molt, 1995). Larsen (1995, 1997) has argued that there is a strong connection between AMTL and periodontal disease in the archaeological context, although it is difficult to specify the cause of AMTL in many cases. Modern clinical studies, however, have pointed out that the main cause of AMTL is dental caries (Ainamo et al., 1984). Caries has been assumed to be the main cause of AMTL in all age categories of those modern populations (e.g. China, Kenya, Tanzania) who do not have a custom of dental care (Baerum and Fejerskov, 1986; Baelum et al., 1988; Manji et al., 1988). In populations accustomed to dental care (e.g. England, Finland, France), the main cause of AMTL up to middle age (<40–50 years old) is dental caries, whereas in the elderly it is periodontal disease (Ainamo et al., 1984; Agerholm and Sidi, 1988; Cahen et al., 1985). Lukacs (2007) has suggested the main causes of AMTL to be as follows: variations in dietary consistency, nutritional deficiency diseases, cultural or ritual ablation, and trauma. In his discussion of diet-derived AMTL, he has proposed three scenarios: (i) dental pulp exposure advances with attrition; (ii) dental caries progresses due to a soft, processed, high-carbohydrate diet; and (iii) a large amount of dental plaque causes gingivitis, and leads to periodontal disease.

Dental caries has been confirmed to be related to sugar intake (Takeuchi, 1962; Newbrun, 1982; Sreebny, 1982; Sheiham, 1983). Turner (1979) examined ancient human populations around the world, and pointed out that the incidence of dental caries increases at the stage of transition from hunting to agriculture, where the average caries rate is 0–5.3% for foraging, 0.4–10.3% for mixed foraging/agriculture, and 2.3–29% for exclusive agriculture people. Studies of North American ancient human populations have reported that the incidence of dental caries increased after contact with Western civilization, or after the introduction of agriculture (Larsen and Thomas, 1982; Larsen, 1983; Lukacs, 1992). In contrast, there are reports that indicate no increase in dental caries before and after the commencement of rice farming agriculture, unlike corn and wheat cultivation society (Tayles et al., 2000; Halcrow et al., 2013).

Studies of oral hygiene in the Jomon people have mainly focused on cases of dental caries, and have indicated that the Jomon people had a high rate of dental caries compared to the other hunter-gatherers; this has been interpreted as due to the Jomon diet being highly dependent on plant resources (Turner, 1979; Fujita, 1995). Furthermore, the sex difference in the dental caries rate reportedly increased in the Late and Final Jomon period, associated with an increase in the degree of the sexual division of labor in food acquisition and its relevant behavior (Fujita et al., 2007; Temple, 2007, 2011; Temple and Larsen, 2007). Inoue et al. (1981) studied periodic shifts in the dental caries frequency from the Late Jomon period, the Middle Ages (Kamakura period), and modern times. They pointed out that the frequency and severity of dental caries were much higher in the Late Jomon period than in the Middle Ages, but the dentognathic discrepancy or malocclusion was less in the Jomon period. This leads to the conclusion that the occurrence of dental caries in the Jomon was more affected by global deterioration due to poor oral hygiene than local accumulation of cariogenic residue by dental dislocation.

On the other hand, only Turner (1979) has collected objective data on periodontal disease for the Jomon people. He investigated the degree of tooth root exposure in 69 Jomon individuals, and pointed out that the frequency of periodontal disease in the Jomon people was as high as that for dental caries and was also higher than the average for hunter-gatherer groups, equivalent to that for a mixed population of agriculturists and hunters. However, the details of the studied specimens were described only as ‘Jomon’ people. In addition to this study, there is a report on the Ohguruwa shell mounds of Aichi prefecture in the Late Jomon period (Inagaki et al., 1991).

Fujita and Suzuki (1995) noted that periodontal disease would have been common in the Jomon population on the basis of observations of Jomon individuals with advanced alveolar resorption and those with neck and root carious, whose teeth roots were presumably exposed from the gingiva at the time of survival. Fujita (1999) indicated that AMTL in the Jomon population was more frequent in the upper dentition than in the lower and that the frequency of the number of dental caries in the upper and lower dentition was the opposite. He argued that most of the maxillary AMTL was due to periodontal disease. In addition, the Jomon population exhibited such a high rate of AMTL compared to that found in the Middle Ages that their oral health environment was possibly worse (Inoue et al., 1981). Although they attributed the cause of this AMTL to dental caries, periodontitis should be considered among the possible main causes.

In order to grasp the state of periodontal disease in the Jomon population, we should observe it on the basis of subjective criteria and integrate those observations into the archaeological context of Jomon site information. In this paper, we aim (i) to calculate the prevalence of periodontal disease in the Jomon population on the basis of subjective and quantitative data; (ii) to investigate the difference in the prevalence between the sexes and local groups; and (iii) to discuss the causes or mechanisms that underlay such differences.
Materials and Methods

We used Jomon skeletal remains from the Ubayama shell-mound in Chiba prefecture, the Nakazuma shell-mound in Ibaraki prefecture, and the Kitamura site in Nagano prefecture (Figure 1). The Ubayama and Nakazuma shell-mounds are in the brackish water system of the Kanto region. Inhabitants from the two sites have reportedly manifested a relatively high rate of dental caries among Jomon populations (Matsumura, 1995; Temple, 2007). In the late half of the Jomon period, the Ubayama shell-mound faced the ‘Old’ Tokyo Bay, and the Nakazuma shell-mound was situated at the innermost shore of the inland gulf (current Kasumigaura) called ‘Old’ Kido Bay. As for the periodontal disease prevalence, there was no mention of that for the Ubayama inhabitants, and that for the Nakazuma inhabitants was assumed to be high in light of the high rate of AMTL (Matsumura, 1995). The Kitamura site is located on a plateau alongside a river in a mountainous region, and its inhabitants were reportedly characterized by having a very low rate of dental caries but without any report of periodontitis or alveolar resorption (Shigehara, 1993, 1994; Temple, 2007).

Table 1 shows the number of study samples and the sex, age, and period breakdowns of individuals. The three Jomon samples belong mainly to the Late Jomon period, although individuals from the Middle Jomon period are included in the Ubayama and Kitamura samples. The associated period, age estimation, and sex diagnosis were mainly based on previous reports or documents (Kondo, 1993; Shigehara, 1993; Matsumura, 1995; Mizushima et al., 2004). Those without records were diagnosed by A.S. on the basis of bone morphology except for the dentition. Age estimation was done by considering the degree of cranial suture closure and epiphysis closure of limb bones or joint surfaces in total, and then individuals were grouped into four age categories of ‘young adult’ (approximately 20–30 years old), ‘early middle-aged’ (30–45 years old), ‘late middle-aged’ (45–60 years old), and ‘elderly old’ (over 60 years old). Sex criteria were based on the morphology of the pelvis and cranium (Seta and Yoshino, 1990; White et al., 2012). As for the age breakdown, the Nakazuma inhabitants include a proportionately smaller number of young adults but a larger number of early middle-aged adults than those of the other two sites, where the between-site difference was significant in the two age categories (\(\chi^2(2) = 7.0, P < 0.05\) in young adults; \(\chi^2(2) = 11.3, P < 0.01\) in early-middle adults). However, when we combined the age categories of young and early-middle, and the late-middle and elderly age groups, we could find no significant difference (\(\chi^2(2) = 0.4, P = 0.82\)). Thus, we finally decided to evaluate the three local samples that had similar age breakdowns and compared them.

Assessment of periodontal disease

Diagnosis of periodontal disease in clinical cases is based on the presence of periodontal intrabony pockets determined through dental probe or X-ray radiography, or based on the inflammation of gums and hemorrhage frequency (Page and Eke, 2007). On the dry bone, it has been assessed by the degree of alveolar bone resorption (Hillson, 1996).

In studies of archaeological human bones, two indicators have been often used for the assessment of jaw bone resorption: the distance from the cement–enamel junction (CEJ) to the alveolar crest (AC); and morphological assessment of inflammation of the interdental septum. The CEJ-AC distance measures the exposure of the root, which can be assessed as the degree of alveolar bone resorption (recession) (Hatano et al., 1986). However, it is known that the root exposure advances with age until about 45 years old (physiological eruption) and also relates to the development of dental wear (Kaifu et

Table 1. Number of individuals in three Jomon populations by sex and age

| Number of samples | Age groups | Period |
|-------------------|------------|--------|
|                   | All        | Male   | Female | Unknown | Young | Early middle | Late middle | Elderly | Unknown | Middle Jomon | Late Jomon | Unknown |
| Nakazuma          | 77         | 47     | 20     | 10      | 7     | 34           | 25          | 2       | 9       | 0             | 77            | 0       |
| Ubayama           | 58         | 33     | 25     | 0       | 14    | 15           | 22          | 2       | 5       | 9             | 43            | 6       |
| Kitamura          | 62         | 26     | 35     | 1       | 21    | 15           | 21          | 5       | 0       | 13            | 23            | 26      |
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| Category | Description |
|----------|-------------|
| Category 0 | Unrecordable, tooth on either side of the septum lost antemortem or the septum damaged postmortem. |
| Category 1 | Septal form characteristic of the region with the cortical surface continuous. Such a situation is considered to represent the ‘healthy’ situation. |
| Category 2 | Septal form characteristic of the region. Cortical surface showing a range from many small foramina and/or grooves to large foramina with prominent grooves or ridges. This category is indicative of inflammation in the overlying soft tissue and a clinical diagnosis of gingivitis. |
| Category 3 | Septal form showing a breakdown of contour, the essential distinguishing feature being a sharp and ragged texture to the bone defect. Such a defect is representative of an acute burst of periodontitis. |
| Category 4 | Septal form showing breakdown of contour, the distinguishing feature being a porous or smooth honeycomb effect with all defects rounded. This defect considered to be a previously acute periodontitis that has reverted to a quiescent phase. |
| Category 5 | Presence of a deep intrabony defect with sides sloping at 45° or more and with a depth of 3 mm or more. This defect is equivalent to a more aggressive periodontitis in either an acute or quiescent phase. |

Previous studies have categorized pathological as being when the CEJ-AC distance exceeds 2 mm (Clarke et al., 1986; Wasterlain et al., 2011; DeWitte, 2012). However, we should consider that a physiological eruption with occlusal wear elongates the distance up to 4 mm on average in the modern population (Tal, 1985; Albandar, 2005), and, as a result, we took a greater threshold of over 4 mm (score 2) as pathological in the present study.

Assessment of the interdental septum morphology was based on Kerr (1988, 1991, 1994) (Table 2). We observed both mesial and distal sides of interdental septum of the preserved dentition and postmortem open socket (Figure 2). In the case adjacent to the AMTL, the septal surface at the AMTL side was not observed. Among the six categories, those equal to or over ‘category 3’ were counted as ‘positive’ inflammation. The mean of the observed scores was used for each individual.

Assessment of other oral health indicators

We observed dental caries, AMTL, occlusal wear, and enamel chipping. Observations of dental caries and AMTL were based on all the preserved dentition. Enamel caries with a destructive concavity were counted as affected but those with only simply colored or ambiguous decalcification were not included. The rate of dental caries (RC) was calculated as the number of caries teeth per the total number of observed teeth. In addition, the average caries frequency per person (ACFP) (Sakura, 1964), which corrects the variable numbers of postmortem tooth loss, was calculated as the following,

$$\text{ACFP} = 2[R\{1\} + R\{2\} + R\{3\} + \ldots + R\{8\}]$$

where $R\{1\}$ = caries rate of the mandibular first incisor.

AMTL was assessed in terms of the degree of dental socket resorption; those with complete or almost complete closure were counted, but those with ambiguous closure were excluded where the antemortem survival of the dentition was plausible. The rate of tooth loss (RTL) was calculated as the number of teeth lost divided by the number of observed sockets, the latter of which includes those with postmortem tooth loss. In addition, we calculated the average tooth loss frequency per person (ATLFP), applying the above-mentioned ACFP calculation for dental caries (Sakura, 1964), as follows:

$$\text{ATLFP} = 2[R\{T\} + R\{2\} + R\{3\} + \ldots + R\{8\}]$$

where $R\{T\}$ = rate of AMTL in the lower first incisor.
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Individual scores were determined after grading the degree of wear of each side of the teeth in the upper and lower jaws separately due to the fact that some individuals showed a significant right–left difference in their dental wear. Enamel chipping was graded on a scale from 0 to 3, which was modified after Bonfiglioli et al. (2004). We scored only on molars and premolars, and used a mean score (total sum of the scores/number of observed teeth) as an individual chipping score. The grades were:

- Grade 0: no chipping
- Grade 1: enamel chipping 1–2 mm in size
- Grade 2: >2 mm size or depth
- Grade 3: a large portion of the cusp was chipped off

Finally, we counted the frequencies in the division of each local sample and of each sex, and compared those for periodontal disease (CEJ-AC distance and alveolar interdental septum), the rate of dental caries, and the rate of AMTL, separately. In addition, we compared the degree of occlusal wear between the local sites and tested the statistical significance by the chi-square test.

Correspondence analysis

In order to analyze relationships between the observed characters or any associations of a trait with a local population and/or sex, we performed a corresponding analysis by using the periodontal scores from the CEJ-AC distance and interdental septum morphology, caries rate, AMTL rate, wear score, and chipping score. Statistical analysis was done using SYSTAT version 13 after categorizing each variable according to the criteria in Table 3.

Results

First we consider the CEJ-AC distance as a measure of periodontal disease. The percentage of individuals whose mean score is ≥2 is 38.6% for the Nakazuma sample, 35.7% for the Ubayama sample, and 31.8% for the Kitamura sample (Table 4), although there is no significant difference between the three samples ($\chi^2(2) = 0.5, P = 0.76$). The percentages of those scores when including the unit of the alveolar socket are 53.6% for Nakazuma, 65.7% for Ubayama, and 49.7% for Kitamura; and the value for Ubayama is significantly higher than the other two ($\chi^2(2) = 28.0, P < 0.01$).

In the assessment of the interdental septum, the individual percentage of those who have a score of ≥3 is 38.8% for the Nakazuma sample, 66.0% for the Ubayama sample, and 60.4% for the Kitamura sample (Table 5). The percentages when including the unit of the interdental septum are 50.5% for Nakazuma, 68.7% for Ubayama, and 64.5% for the Kitamura samples. In these two cases, the Nakazuma inhab-

![Figure 2. Five categories of interdental septum morphology. All specimens are selected from the samples in this study.](image)

| Categorizing score | 1     | 2     | 3     | 4     | 5     |
|--------------------|-------|-------|-------|-------|-------|
| Average value of the CEJ-AC distance $^1$ scores | $x = 0$ | $0 < x \leq 1$ | $1 < x \leq 2$ | $2 < x \leq 3$ | $3 < x$ |
| Average value of the interdental septum morphological scores | $0 < x \leq 1$ | $1 < x \leq 2$ | $2 < x \leq 3$ | $3 < x \leq 4$ | $4 < x \leq 5$ |
| Caries rates | $x = 0\%$ | $0 < x \leq 0.25$ | $0.25 < x \leq 0.5$ | $0.5 < x \leq 0.75$ | $0.75 < x \leq 1$ |
| Rates of AMTL $^2$ | $x = 0\%$ | $0 < x \leq 0.25$ | $0.25 < x \leq 0.5$ | $0.5 < x \leq 0.75$ | $0.75 < x \leq 1$ |
| Wear | A | B | C | D | E |
| Average value of the chipping scores | $x = 0$ | $0 < x \leq 0.5$ | $0.5 < x \leq 1$ | $1 < x \leq 1.5$ | $1.5 < x$ |

$^1$ CEJ-AC distance is the distance between the cement–enamel junction and the alveolar crest.
$^2$ AMTL, antemortem tooth loss.

the Kitamura Jomon individuals (Shigehara, 1993, 1994). Individual scores were determined after grading the degree of wear of each side of the teeth in the upper and lower jaws.
itants exhibit significantly lower rates of positive periodontal disease than the other two samples ($\chi^2(2) = 10.1, P < 0.05$ for individual count; $\chi^2(2) = 30.6, P < 0.01$ for interdental septum count).

Between sexes, the percentage of affected individuals shows no significant sex difference in either the CEJ-AC distance or the interdental septum. However, the percentage of the males is higher than that of the females in general. A significantly higher male rate is found in the Kitamura sample in the CEJ-AC distance when including the unit of the alveolar socket ($\chi^2(1) = 20.4, P < 0.01$). A higher male rate is also found in both the Nakazuma and Kitamura samples in the interdental septum assessment when including the unit of the interdental septum ($\chi^2(1) > 68.0, P < 0.01$ for Nakazuma; $\chi^2(1) > 68.0, P < 0.01$ for Ubayama). The Kitamura samples show no sex difference.

The rate of dental caries is 17.0% for Nakazuma, 11.4% for Ubayama, and 1.9% for Kitamura, where the differences between the three samples are statistically significant ($\chi^2(2) = 92.4, P < 0.01$, Table 6). Sex differences are significant in the Nakazuma and Ubayama samples: females were more susceptible to having carious teeth ($\chi^2(1) > 68.0, P < 0.01$ for Nakazuma; $\chi^2(1) > 68.0, P < 0.01$ for Ubayama). The Kitamura samples show no sex difference.

The rate of AMTL is 8.8% for Nakazuma, 10.8% for Ubayama, and 3.7% for Kitamura, respectively, and that for Kitamura is significantly lower than the other two ($\chi^2(2) = 9.8, P < 0.01$).

### Table 4. Percentage of periodontal disease evaluated by the distance from the cement–enamel junction to the alveolar crest (Individual scores)

|          | Nakazuma |          | Ubayama |          | Kitamura |
|----------|----------|----------|---------|----------|----------|
|          | $n$      | Score ≥2 | %       | $n$      | Score ≥2 | %       | $n$      | Score ≥2 | %       |
| All      | 70       | 27       | 38.6%   | 66       | 20       | 35.7%   | 44       | 14       | 31.8%   |
| Male     | 45       | 23       | 51.1%   | 32       | 11       | 34.4%   | 21       | 9        | 42.9%   |
| Female   | 14       | 3        | 21.4%   | 24       | 9        | 37.5%   | 23       | 5        | 21.7%   |

(Including alveolar socket)

|          | Nakazuma |          | Ubayama |          | Kitamura |
|----------|----------|----------|---------|----------|----------|
|          | $n$      | Score ≥2 | %       | $n$      | Score ≥2 | %       | $n$      | Score ≥2 | %       |
| All      | 330      | 177      | 53.6%   | 624      | 410      | 65.7% **| 362      | 180      | 49.7%   |
| Male     | 237      | 148      | 62.4%   | 383      | 258      | 67.4%   | 211      | 129      | 61.1% **|
| Female   | 64       | 29       | 45.3%   | 251      | 160      | 63.7%   | 151      | 56       | 37.1% **|

** $P < 0.01; * P < 0.05.$

### Table 5. Percentage of periodontal disease evaluated by the condition of the interdental septa (Individual scores)

|          | Nakazuma |          | Ubayama |          | Kitamura |
|----------|----------|----------|---------|----------|----------|
|          | $n$      | Category ≥3 | %       | $n$      | Category ≥3 | %       | $n$      | Category ≥3 | %       |
| All      | 67       | 26       | 38.8% * | 53       | 35       | 66.0%   | 48       | 29       | 60.4%   |
| Male     | 44       | 17       | 38.6%   | 32       | 20       | 62.5%   | 20       | 11       | 55.0%   |
| Female   | 15       | 5        | 33.3%   | 21       | 15       | 71.4%   | 27       | 17       | 63.0%   |

(Including alveolar septum)

|          | Nakazuma |          | Ubayama |          | Kitamura |
|----------|----------|----------|---------|----------|----------|
|          | $n$      | Category ≥3 | %       | $n$      | Category ≥3 | %       | $n$      | Category ≥3 | %       |
| All      | 408      | 206      | 50.5% **| 575      | 395      | 68.7%   | 259      | 167      | 64.5%   |
| Male     | 280      | 147      | 52.5% * | 364      | 242      | 66.5%   | 120      | 87       | 72.5% * |
| Female   | 94       | 45       | 47.9%   | 211      | 153      | 72.5%   | 137      | 78       | 56.9% * |

** $P < 0.01; * P < 0.05.$

### Table 6. Percentage of caries by site and sex

|          | Nakazuma |          | Ubayama |          | Kitamura |
|----------|----------|----------|---------|----------|----------|
|          | $n$      | Carious teeth | % | ACFP$^1$ | $n$  | Carious teeth | % | ACFP$^1$ | $n$  | Carious teeth | % | ACFP$^1$ |
| All      | 594      | 101       | 17.0% **| 1.30     | 1183 | 135       | 11.4% **| 0.90     | 780 | 15       | 1.9% ** | 0.11     |
| Male     | 423      | 49        | 11.6% **| 0.90     | 699  | 30        | 4.3% ** | 0.30     | 397 | 6        | 1.5%    | 0.09     |
| Female   | 132      | 46        | 34.8% **| 2.70     | 484  | 105       | 21.7% **| 1.80     | 379 | 9        | 2.4%    | 0.13     |

** $P < 0.01; * P < 0.05.$

$^1$ ACFP, average caries frequency per person (Sakura, 1969).
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57.4, \( P < 0.01 \), Table 7). Sex differences are commonly found in the three samples: females show more AMTL than males (\( \chi^2(1) = 68.0, P < 0.01 \) for Nakazuma; \( \chi^2(1) = 42.5, P < 0.01 \) for Ubayama; \( \chi^2(1) = 18.2, P < 0.05 \) for Kitamura).

The degree of occlusal wear is considered as an age indicator. In order to check the consistency of the age–wear relation among groups, the wear degree of each age category is compared among the three sites. In young adults, grade A is abundant in all the three groups and the proportion of grade A/B–E individuals is not significantly different (\( \chi^2(2) = 2.1, P = 0.35 \)). In the Nakazuma sample, grade A is still abundant in early-middle adults, and grades A–B occupied a relatively large portion in late-middle adults. The Kitamura sample includes comparatively more grade B individuals in early-middle adults and also more grades C–D individuals in late-middle adults. The Ubayama sample contains more grade D individuals in early-middle adults and more grade E individuals in late-middle adults. Significant differences are found in the two comparisons of early-middle (\( \chi^2(6) = 28.1, P < 0.01 \)) and late-middle adults (\( \chi^2(6) = 18.5, P < 0.01 \)). In sum, the rate of occlusal wear is more advanced in the Ubayama sample, slow in the Nakazuma sample, while that of the Kitamura sample is intermediate between the two. Sex differences were not significant within each local sample.

The frequency for each CEJ-AC distance score (Figure 3) and for the interdental septum category (Figure 4) are presented with divisions for each age category and sex. These are based on the counts for the unit of each dentition or each septum, respectively. Sex differences within each site are small. The pattern of the age-related shift of the frequencies is also common to both the CEJ-AC distance and the interdental septum. However, those between the three sites are different; those for Kitamura and Nakazuma show more high scores with advanced age, indicating more individuals with periodontal disease; in contrast, those for Ubayama exhibit more high-score individuals even in young adults. In the Ubayama females, the frequency of periodontal individuals decreases from early-middle to late-middle adults. This

** Table 7. Percentage of antemortem tooth loss (AMTL) by site and sex

| Site    | Sample | n  | AMTL | ATLFP | ATLFP* |
|---------|--------|----|------|-------|--------|
|         | Male   |    |      |       |        |
| Nakazuma| 713    | 50 | 7.0% | 0.60  | 1.10   |
| Ubayama | 868    | 54 | 6.2% | 0.50  | 1.40   |
| Kitamura| 566    | 38 | 0.9% | 0.35  | 0.30   |
|         | Female |    |      |       |        |
| Nakazuma| 273    | 38 | 13.9%| 1.10  | 1.10   |
| Ubayama | 703    | 116| 16.5%| 1.00  | 1.40   |
| Kitamura| 586    | 38 | 6.5% | 0.35  | 0.30   |

** \( P < 0.01 \); * \( P < 0.05 \).

\( ^1 \) ATLFP, average tooth loss frequency per person defined in this study according to the method used by Sakura (1969).

![Figure 3](image)

Figure 3. Frequency of the CEJ-AC distance score in age groups. The thick black lines indicate the proportion with a score ≥2 (rates that exceed moderate periodontal disease). The elderly groups were excluded because of the small number of samples.
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is assumed to be relevant in terms of the increase in unobservable dentition or dental septum due to AMTL.

A corresponding analysis was conducted in order to visualize the inter-site, sexual, and age-related variations based on the two periodontal observations and the other oral health indicators (occlusal wear, AMTL rate, caries rate, and chipping score) (Figure 5, Figure 6, Figure 7). In the plot of the inter-site variation (Figure 5), the first axis represents 85.1%, and the second axis represents 14.9% of the total variation, respectively. Figure 4 shows the inter-site variation of the six groups, divided by sex, where the first axis represents 61.6% and the second axis represents 25.0% of the total variation. In both plots, the traits of ‘wear’ and ‘chipping’ are plotted on the right, and the ‘caries’ and ‘AMTL’ on the left. The first axis generally indicates the effect of functional load in the positive direction and that of infectious alteration in the negative direction.

In Figure 5, the second axis helps to visualize the inter-site variation. The Ubayama sample is characterized by the frequencies of ‘AMTL’ and ‘wear,’ Nakazuma by ‘caries’ and ‘AMTL,’ and Kitamura by ‘chipping’ and ‘wear.’ In the sex-divided plot (Figure 6), the CEJ-AC distance is plotted in the upper position, and ‘AMTL,’ ‘wear,’ and ‘caries’ are plotted in the lower position along the second axis. The second axis depicts the sexual difference, where males are directed to the upper right corner and females to the lower left corner with minor differences in each site. Thus, the traits of the ‘CEJ-AC distance,’ ‘septum,’ and ‘chipping’ can be considered male, and those of ‘caries’ and ‘AMTL’ as female.

Taking the variation of the six subsamples into consideration, the range of inter-sex variation is similar to that of inter-site variation. In addition, the inter-site variation is

Figure 4. Frequency of the interdental septum categories in age groups. The thick black lines indicate the proportion with a score of ≥3 (rates that exceed moderate periodontal disease). The elderly groups were excluded because of the small number of samples.

Figure 5. Correspondence analysis of the three populations using six oral health indicators.
larger in females than in males. The sex difference is small-est in Kitamura, and becomes larger in Ubayama and Naka-zuma.

As for the two traits of periodontal disease, the position of the ‘CEJ-AC distance’ falls near the ‘caries’ and ‘AMTL’ on the left side, both of which are assumed to be related to the presence of infectious or alien agents. In the sex-divided plot, the item of ‘CEJ-AC distance’ is positioned away from the other five items in the upper area along the second axis. It is the most distant from the ‘wear,’ which has been indicated as the most relevant to each other in previous studies (Murphy, 1959; Newman and Levers, 1979; Whittaker et al., 1985; d’Incau et al., 2012). The trait of ‘interdental septum’ is plotted to the right of the center. Although it cannot be easily distinguished among the six groups, it is assumed to be relevant to the functional loads, such as ‘chipping’ or ‘wear,’ as compared to the case of the ‘CEJ-AC distance.’

We should note, however, that the two periodontal disease items, both of which fall near the origin of the center, do not clearly exhibit inter-site variation, and thus the relevance to the other items may be secondary.

Finally, the plot of sex- and age-divided groups (Figure 7) apparently exhibits an age change along the first axis and a sex difference along the second axis. The shift with age can be detected in both sexes as it goes from the ‘chipping’ abundant stage to the ‘wear’ advanced stage during the period from adult to elderly. An insufficient number for the male elderly group (M4) may explain a bias in the scores, which moves it to the left (negative) in the plot. The position of ‘wear’ on the positive end along the first axis might be due to the high degree of relevance in terms of the amount of ‘wear’ to age. Polychoric correlation coefficients between the ‘wear’ score and age in the present study are 0.67 ($T = 10.2, P < 0.01$) in males and 0.81 ($T = 16.1, P < 0.01$) in females. The distant position of the ‘CEJ-AC distance’ from the ‘wear’ is consistent with the result seen in the inter-site plot (Figure 5). The traits relevant along the second axis are the ‘CEJ-AC distance,’ ‘caries,’ and ‘AMTL.’ Among these, ‘CEJ-AC distance’ is seemingly attributable as a male characteristic, whereas ‘caries’ and ‘AMTL’ are associated with females. This consideration is consistent with the sex- and site-divided plot of the six samples (Figure 6).

**Discussion**

The rate of periodontal disease in Jomon individuals was calculated at 31.8–38.6% based on the assessment of the CEJ-AC distance, and 38.8–66.0% based on evaluation of the interdental septum. Turner (1979) observed 69 Jomon individuals and reported 34.8% (24 individuals) as having moderate or severe periodontal disease. The result in the present study is admittedly similar to that of Turner (1979), considering that the limited observation on the molar teeth in the present study might decrease the periodontal counts.

Previous studies of other hunter-gatherers have reported moderate or severe periodontal disease. One such example reported 47.7% and 44.6% for Alaskan Eskimo samples from Tigara and Ipiutak, respectively, 33.9% for Australia aborigines, and 46% for the prehistoric Native Californian CA-Ala-329 site (Costa, 1982; Jurmain, 1990; Littleton, 2018). However, for a different site (CA-CCO-548) in prehistoric Native California a lower rate of 17.8% has been recorded (Griffin, 2014). By comparing these, the periodontal disease rate for the Jomon population can be considered as moderate compared with the other hunter-gatherer popu-lations.

The periodontal disease rate in each of the three Jomon populations exhibits a smaller inter-site and sex variation
than those of caries or AMTL rate. The percentage of individuals or teeth with periodontitis judged by the CEJ-AC distance was similar among the three samples. On the other, in comparison with the interdental septum inflammatory traits, the affected rate was seemingly higher in the group with strong occlusal wear (Ubayama and Kitamura) than in the group with weak occlusal wear (Nakazuma). In addition, the prevalence rate for each age category was higher in the strong wear group of Ubayama, where even the young-aged individuals exhibited periodontitis (Figure 3, Figure 4). In the plot of corresponding multivariate analysis, the dental septum was relevant in terms of the ‘wear’ and ‘chipping’ traits, which was assumed to correspond to mechanical loadings, and the CEJ-AC distance was relevant in terms of the ‘AMTL’ and ‘caries’ traits (Figure 6). These indicate that the mechanical loads associated with ‘wear’ and ‘chipping’ possibly caused damage due to the periodontal tissues and advanced periodontal disease conditions.

A previous study of aboriginal Australians investigated the associations between occlusal wear and oral health indicators (caries, calculus, pulp exposure, periapical voids, periodontitis) (Littleton, 2018). The results indicated that occlusal wear showed the highest associations with pulp exposure and periapical voids, as well as showed a moderate association with periodontitis; only periodontitis showed positive associations with four of five items (all except caries). Littleton (2018) assumed that the effect of occlusal wear on periodontal disease was a non-direct, secondary one, between which the aging effect had intervened. In fact, as the degree of occlusal wear relates well with age, it is difficult to judge whether it is the occlusal wear or the age that has the stronger effect on the prevalence of the periodontal disease. In the present study, however, the population with strong occlusal wear, i.e. Ubayama, exhibited more individuals with interdental septum inflammation even in young adults. Clarke and Hirsch (1991) discussed damage to the periodontal tissue due to the progression of occlusal wear, and linked moderate to severe progression of periodontal disease with exposure of the dental pulp and the presence of periodontal inflammation. In addition, occlusal trauma and excessive occlusal force are reported to promote periodontal disease (Harrel, 2003; Harrel et al., 2006; Fan and Caton, 2018).

In sum, we may hypothesize the following process: a locally limited alveolar recession (periapical voids) due to strong occlusal wear at the onset grows with daily incremental loads, which results in the accumulation of micro-damage in the periodontal tissue and the expansion of inflammation into a wider range of periodontal disease.

The observed association between CEJ-AC distance and caries is plausibly ascribed to a tendency in which the dentition with a greater CEJ-AC distance exposes a larger portion of dentine and thus becomes prone to suffer caries. The association of this with AMTL is also plausible, where a greater CEJ-AC distance from the alveolar recession or occlusal wear easily contributes to tooth loss.

The two indicators of periodontal disease, CEJ-AC distance and interdental septum, express the different characteristics mentioned above. As pointed out in previous studies, the assessment of the interdental septum, not of the CEJ-AC distance, seemingly reflects more directly on the periodontitis or its associated alteration in the present study.

Next, we discuss the result based on other oral health indicators. The three local Jomon samples in the present study exhibited different patterns in the rates of dental caries, AMTL, and the degree of occlusal wear, all of which are significantly different among the three samples. The Nakazuma sample showed higher rates of dental caries and AMTL and a lower degree of occlusal wear. The Ubayama sample also showed higher rates of caries and AMTL, but an advanced degree of occlusal wear and higher periodontitis. The Kitamura sample showed lower rates of caries and AMTL but a moderate degree of occlusal wear and periodontitis.

We can assume diet in general as a plausible factor responsible for the different rates of dental caries among the local samples. Recent stable isotope analyses have reported on the dietary patterns of inhabitants for each Jomon site (Yoneda, 2008, 2014). The Ubayama and Nakazuma inhabitants had proportionately well-balanced diets ranging from terrestrial flora and fauna to marine products; the Kitamura inhabitants mainly depended on a terrestrial C3 plant-based ecosystem, including terrestrial herbivores. Approximately 54–70% of their diet was assumed to be animal protein (Naito et al., 2013). These dietary discrepancies may be the cause of the observed inter-site difference in the dental caries and AMTL rates between Kitamura and the other two Jomon sites. These latter two sites, Ubayama and Nakazuma, however, exhibited several differences in oral health indicators, although these two sites are both coastal shell-mounds, close in proximity and similar in diet. Ubayama had a slightly higher periodontal disease rate and Nakazuma was higher in caries rate. The difference in the periodontal disease rate is assumed to be due to the effect of the different degree of occlusal wear as explained above. On the other, the reason for the caries rate difference is obscure. In this regard, we noticed in the corresponding multivariate analysis that the degree of inter-sex difference was similar to that of the inter-site difference. The inter-site difference among the three sites was greater in females than in males. In terms of univariate comparison, the caries rate and the AMTL rate were conspicuous in terms of the sexual difference. In contrast, the stable isotope proxy for the diet has been reported to be similar in terms of sex and age for each Jomon site (Yoneda, 2008, 2014).

The reason for the inter-site or inter-sex difference observed in the oral health indicators seems to be ascribed to other factors, such as dietary resource differences, that were undetectable in the stable isotope study, sex hormonal variation due to pregnancy or childbirth, diet frequency and/or different cooking methods, etc. In particular, although Nakazuma and Ubayama are both shell-midden sites, their geographical locations are somewhat different. The Nakazuma site is situated in the innermost shore of Old Kido Bay (inner bay), and the Ubayama site faces Tokyo Bay (outer bay). As a result of the sea recession seen in the Late Jomon period, the opening of Old Kido Bay to the outer sea seemingly narrowed, and then a wide brackish tidal flat moved around the Nakazuma site (Kamei, 2018). Faunal identification of the Nakazuma site revealed the abundance of small-sized fish.
such as eel and goby, which had adapted to the transition from brackish water to freshwater; and brackish-water shellfish such as Japanese basket clams (Corbicula japonica) were dominant (Toizumi, 2018). In addition, large oceanic fishes such as red seabream (Sparidae) or globefish (Tetraodontidae) were identified, the presence of which are assumed to be outcomes of the open-ocean fishery or trade with neighboring communities. Wildlife hunting was also assumed to take place from the Late to Latest Jomon period, and cervids were abundant at the Nakazuma site in particular.

On the other hand, the eastern coast of Tokyo Bay has reportedly yielded many large-scale shell-midden sites, including Ubayama. It has been assumed that the area was densely populated in the Late Jomon period because large shell-mounds were found at about 2 km intervals (Horikoshi, 1972). The diet of the people and their relevant behavior were seemingly rich in variety based on the faunal and floral remains, lithic assemblage variation, and increase in the number of storage pits, etc. It has been pointed out that Jomon inhabitants used edible roots and nuts, forest resources such as deer and wild boar, and marine resources such as small fishes, snails (Umbonium moniliferum), and clams (Meretrix lusoria) (Nishino, 2009; Abe, 2014). This information tells us that a possibly different population pressure existed between the two Jomon sites, and thereafter they possessed different levels of both food competition and labor division. These factors may provide reasons behind the sex difference.

In terms of wild plant utilization, evidence has yet to be provided that the Nakazuma inhabitants used edible root vegetables or nuts, although their caries rate was high. In the large area of the Kanto region in the Late Jomon period, however, several kinds of controlled cultivation have been confirmed, such as the management of chestnut and urushi, Japanese walnut, horse chestnut, or Quercus, beans such as azuki and soybean, and sesame, gourd, and cannabis, etc., all of which were cultivated to a significant degree (Sasaki, 1972; Kudo and Sasaki, 2010). Jomon inhabitants appear to have selected a breed with large-sized edible part, construct a kind of equipment to remove the bitterness, and actively used a variety of wild plants (Noshiro and Sasaki, 2014). The difference in the dental caries rate between Nakazuma and Ubayama, which remains to be clarified, may be ascribed to yet undetected dietary variations related to the use of wild plants.

**Conclusions**

This study assessed the periodontal disease in three populations of the Late Jomon period from the Kanto and central Honshu regions through an analysis of the CEJ-AC distance and inflammation of the interdental septum. The results indicated that 31.8–66.0% of the individuals had a moderate or severe periodontal condition. The inter-site or inter-sex differences among the three Jomon populations were smaller in the periodontal disease rate than in the other oral health indicators of caries, i.e. AMTL, occlusal wear, and chipping. On the basis of interdental septum assessment, populations with higher occlusal wear exhibited higher rates of periodontal disease. In addition, corresponding multivariate analysis using all the observed traits indicated a different aspect of the observed periodontal disease from those of previous studies, namely a stronger relation with interdental septum inflammation, but not with CEJ-AC distance, in terms of the degree of occlusal wear. This presumably indicates a more direct effect of occlusal wear on the inflammation of the periodontal tissue.

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