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Dental Caries Prevalence as Evidence for Agriculture and Subsistence Variation During the Yayoi Period in Prehistoric Japan: Biocultural Interpretations of an Economy in Transition

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KEY WORDS bioarchaeology; dental caries; Yayoi; Japan; rice agriculture; dental anthropology

ABSTRACT The Yayoi period represents the earliest point of agricultural dependence in Japan, dating from ~2500 BP to AD 300. Yayoi period people consumed wet-rice as a primary subsistence base. This article uses dental caries prevalence to interpret the biocultural implications of agriculture among these people by testing the following hypotheses: 1) Yayoi period agriculturalists had greater frequencies of carious teeth than Jomon period foragers, 2) regional variation in carious tooth frequencies will be observed among Yayoi period agriculturalists, while 3) variation in carious tooth frequencies will be observed between male and female agriculturalists. Statistically significant differences in carious teeth were observed between the agriculturalists from Southern Honshu and all other samples. These differences suggest greater reliance on cariogenic plants among farmers from Southern Honshu and are consistent with an agricultural economy. The people of the Yayoi period from Tanegashima Island and Northern Kyushu did not have significantly different carious tooth frequencies compared to Jomon period foragers. This suggests that rice alone was not a more cariogenic dietary substance than those consumed by Jomon period foragers but a cariogenic food nonetheless. Dietary heterogeneity between the prehistoric people of the Yayoi period from Southern Honshu and those from Northern Kyushu and Tanegashima Island is also inferred from these differences. Significantly greater frequencies of carious teeth among older aged Yayoi period females compared with males suggest dietary differences between the sexes. Am J Phys Anthropol 134:501–512, 2007.

This article documents and interprets patterns of variation in dental caries prevalence among prehistoric farmers from Yayoi period Japan. People of the Yayoi period (c. 2500 BP to AD 300) were the earliest agriculturally dependent group in Japanese prehistory, relying on wet rice as a primary subsistence base (Imamura, 1996a,b). These prehistoric farmers migrated to Japan from the Asian continent and bred with indigenous Jomon era foragers (Hanihara, 1991). Migrants to Japan during the Yayoi period are hypothesized to have arrived from China, Korea, or Siberia (Brace and Nagai, 1982; Hanihara, 1991; Nakahashi, 1993; Omoto and Saitou, 1997; Iiuzuka and Nakahashi, 2002). The earliest occupations of Japan by Yayoi period migrants includes Southern Honshu, Northern Kyushu, and later, Tanegashima Island (Fig. 1).

The relationship between oral health and diet has been demonstrated in archaeological settings, particularly during the transition to maize based agriculture or subsistence changes among prehistoric foragers (e.g., Turner, 1979; Milner, 1984; Ubelaker, 1984; Walker and Erlandson, 1986; Larsen et al., 1991; Rose et al., 1991; Lukacs, 1992; Pilloud, 2005; Temple, 2006). In Japan, Yayoi period agriculturalists have greater carious tooth frequencies than foragers from the Jomon period (Sanui, 1960; Inoue et al., 1986; Oyamada et al., 1996; Todaka et al., 2003). Variation in carious teeth between Yayoi period farmers from different environments is also reported (Todaka et al., 2003). However, the primary goal of the Todaka et al. (2003) article was to help explain changes in dietary behavior that occurred after the arrival of Asian migrants to the Japanese islands. This article differs from that of Todaka et al. (2003) by discussing dental caries prevalence within the context of Yayoi and Jomon period dietary choices and explaining how these choices are associated with variation in oral physiology. A discussion on how variation in dental caries prevalence helps support hypotheses about the types of subsistence economies associated with the Jomon and Yayoi periods is also included. Furthermore, variation in carious tooth frequencies observed between the Jomon and Yayoi periods is discussed within the context of other regional studies of caries prevalence, particularly in Southeast Asia, focusing on the relationship between rice dependence and oral health. Specifically, this study tests the hypothesis that the agriculturally

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Fig. 1. Map of Japan illustrating the approximate locations of the sites used by this study. Yayoi period sites are listed with letters. Jomon period sites are listed with numbers. A. Hirota; B. Torinomine; C. Kanenokuma; D. Nagaoka; E. Doigahama; F. Koura. 1. Yosekura; 2. Tsukumo; 3. Inariyama; 4. Yoshigo; 5. Hobi; 6. Nakazuma.

dependent economies of the prehistoric Yayoi period were associated with greater frequencies of carious teeth when compared to Jomon foragers, and that the frequencies of carious teeth among Yayoi period people from different regions varied in association with differential patterns of food consumption.

This article also explores how the subsistence choices of the Yayoi period resulted in variation in caries prevalence between the sexes. Sex differences in frequencies of carious teeth have been documented in a variety of settings, often with females having greater caries prevalence than males in association with a sexual division of labor (Larsen, 1983; Kelley et al., 1991; Larsen et al., 1991; Cohen and Bennett, 1993; Lukacs and Pal, 1993; Lukacs, 1996). Hunting behavior among men may afford them greater access to less cariogenic meat products, whereas plant care/gathering behavior among women is associated with greater consumption of cariogenic plant foods.

The relationship between dental caries prevalence and the sexual division of labor has been further documented among living agrarian and horticultural people from Africa (Walker and Hewlett, 1990). A lack of differences in carious teeth between males and females among living South American horticulturalists is associated with a lesser degree of sex based dietary variation (Walker et al., 1998). These findings suggest that sex based differences in carious tooth frequencies reflect differential consumption of cariogenic foods between men and women attendant with a sexual division of labor. This study, therefore, tests the hypothesis that greater frequencies of carious teeth will be observed among Yayoi period females compared to males.

BIOCULTURAL CONTEXT

Evidence for plant domestication and agricultural economies is well documented in the Yayoi period. For example, more than 100 Yayoi era rice paddies have yielded opal strands belonging to *Oryza sativa japonica*, the domesticated species of Japanese wet rice (Crawford, 1992). Archaeological documentation of well preserved rice fields demonstrates agricultural ecosystems during the Yayoi period whose maintenance required significant energy expenditure (Imamura, 1996b; Tsude, 2001). Dietary reliance on domesticated rice is also supported by isotopic ratios derived from human skeletal remains that suggest Yayoi era farmers consumed the same staple food product (Chisholm and Koike, 1999). The staple food product consumed by Yayoi period people had a high δ^{15}N value indicating that it was grown in a wet environment (Chisholm and Koike, 1999).

Archaeological research indicates that migrants from continental Asia introduced wet rice agriculture to the Japanese islands (Imamura, 1996b; Tsude, 2001); however, people of the Jomon period domesticated many types of plants before the arrival of Asian migrants (Crawford, 2006). The earliest dates for migrant arrival correspond with the earliest dates for wet rice production in Northern Kyushu and Southern Honshu, specifically those obtained from the Doigahama, Itatzuke, and Notame sites (Imamura, 1996b). Tool types and irrigation systems that closely resemble those found at farming sites from southern China and Korea also suggest that wet-rice agriculture was brought to Japan by migrant populations (Tsude, 2001).

The arrival of migrants from the Asian continent as fully functioning agriculturalists represents a transitional economy for the Japanese islands insofar as prehistoric foragers from the Jomon period became active participants in wet rice based economies. This hypothesis is supported by evidence for trade between Jomon and Yayoi groups combined with a gradual adoption of agricultural lifestyles among the Jomon period people in eastern Japan ~200 years after the introduction of these economies to the Japanese islands (Akazawa, 1981).

Reductions of tooth and jaw size follow post-Pleistocene dietary changes (Kieser, 1990; Larsen, 1997). Experimental studies demonstrate that less coarse diets are conducive to a decrease in alveolar prognathism (Lieberman et al., 2004). The origin of agriculture in Japan coincides with changes in cranio-dental morphology recorded around 2500 BP (Imamura, 1996a). Wet rice economies introduced a less coarse dietary staple to the Japanese islands (Fujita, 1993; Todaka et al., 2003). The general changes in cranio-facial form attendant with the Yayoi period were originally thought to indicate morphological change in response to wet rice agriculture (Suzuki, 1969). This dietary change is, however, associated with an increase in alveolar prognathism (Kaifu, 1999). Additionally, both increased tooth and jaw size are observed among Yayoi period agriculturalists when compared with foragers from the Jomon period (Brace and Nagai, 1982; Matsumara, 1995; Kaifu, 1995, 1997). These findings suggest that either 1) the people of the Yayoi period represent a new trend in evolutionary history that defies modern human tooth and jaw size trajectories or 2) new genes introduced to the Japanese islands are associated with this morphological trend. Studies of ancient and recent DNA suggest that the "mi-

TABLE 1. Sites, dates, and locations of the skeletal materials utilized by this study

Site	Period	Dates	Location	Collection
Doigahama	Early to Middle Yayoi	2500–1900 BP	Southern Honshu	Univ. of Kyushu[a]
Koura	Middle to Late Yayoi	1900–1700 BP	Southern Honshu	Univ. of Kyushu
Kanenokuma	Middle Yayoi	2100–1900 BP	Northern Kyushu	Univ. of Kyushu
Nagaoka	Middle Yayoi	2100–1900 BP	Northern Kyushu	Univ. of Kyushu
Torinominae	Middle to Late Yayoi	2100–1700 BP	Tanegashima Island	Univ. of Kyushu
Hirota	Middle to Late Yayoi	2100–1700 BP	Tanegashima Island	Univ. of Kyushu
Hobi	Final Jomon	3000–2300 BP	Tokai	UMUT[b]
Inariyama	Late to Final Jomon	4000–2300 BP	Tokai	Univ. Kyoto[c]
Nakazuma	Late Jomon	4000–3000 BP	Kanto	Toride Board[d]
Tsukumo	Late to Final Jomon	4000–2300 BP	Chugoku	Univ. Kyoto
Yosekura	Late Jomon	4000–3000 BP	Chugoku	UMUT
Yoshigo	Late to Final Jomon	3400–2300 BP	Tokai	Univ. Kyoto

[a] School of Basic Human Structures, University of Kyushu.
[b] University Museum, University of Tokyo.
[c] Laboratory of Physical Anthropology, University of Kyoto.
[d] Toride Board of Cultural Assets.

grant people" of the Yayoi period represent a group of individuals who arrived in Japan from the Asian continent and bred with some Jomon foragers (Omoto and Saito, 1997; Hammer et al., 2006). General variation in the appearance of later Kofun and historic Japanese compared with people of the Yayoi period suggest behaviorally related changes in morphology after the arrival of these migrants to the Japanese islands (Mizoguchi, 1986).

Hypotheses that invoke a bio-behavioral basis for these changes in morphology are consistent with studies of dental caries between the people of the Yayoi period and agriculturalists from Neolithic China. Significantly greater frequencies of carious teeth were observed among the Yayoi people compared to several groups from Neolithic China (Todaka et al., 2003). This increase in carious tooth frequency indicates that the Yayoi underwent a dietary change after arriving in Japan (Todaka et al., 2003). These changes in subsistence economy are associated with variation in cranio-facial morphology among the Kofun and other historic people of Japan compared to the Yayoi (Mizoguchi, 1986). The specific changes in dietary behavior after the arrival of continental Asian migrants to the Japanese islands are not well understood because the specific geographic origin of these migrants is still open to question. However, local changes in cranial morphology (Mizoguchi, 1986) in combination with greater frequencies of carious teeth compared to farmers from the Asian continent (Todaka et al., 2003) suggest that a dietary change took place subsequent to the arrival of these migrants to the Japanese islands.

MATERIALS

Carious teeth were recorded from the dental remains of individuals recovered from six Early to Late Yayoi period (2500–1300 BP) sites (Fig. 1; Table 1). Human skeletal remains from Southern Honshu, Northern Kyushu, and Tanegashima Island are used in this study. The skeletal samples were recovered from Doigahama, Koura, Kanenokuma, Nagaoka, Hirota, and Torinomine. These remains are curated by the Physical Anthropology Museum at Kyushu University, Fukuoka, Japan. All of the sites were dated using pottery based chronology and radiocarbon methods.

Comparative samples were derived from six Late to Final Jomon period (c. 4000 to 2300 BP) sites (Fig. 1; Table 1). These sites were dated using pottery chronology and radiocarbon methods. The use of pottery chronology is an accurate method by which to estimate site occupations because of the systematic methods used to date Jomon pottery (see reviews by Aikens, 1995; Imamura, 1996a; Habu, 2004). A portion of the Tsukumo and all of the Yoshigo and Inariyama Jomon are curated by the Laboratory of Physical Anthropology at Kyoto University, Kyoto, Japan. All of the Hobi and Yosekura as well as a portion of the Tsukumo skeletal material is curated by the Department of Physical Anthropology and Prehistory at the University Museum, University of Tokyo. Individuals from Nakazuma are curated by the Department of Cultural Assets of Toride City.

METHODS

Dental caries is a disease process associated with focal enamel demineralization by organic acids (Larsen, 1997). Organic acids are produced by bacteria that consume food particles in the oral cavity. Carious lesions were identified based on enamel demineralization in stages that ranged from destruction of more than half of a total tooth involving adjacent teeth to pin-prick sized lesions. Carious lesions were identified under diffuse fluorescent lighting and a 100-W desk lamp with a 10× magnifying glass and a dental mirror. A dental mirror was used to help improve observations of carious lesions on distal and mesial tooth surfaces by providing vantage points that are difficult to obtain using simple macroscopic observation. Frequencies of carious teeth were calculated as the total number of teeth in each tooth group with at least one observable carious lesion divided by the total number of teeth in each tooth group. It is, however, important to point out that carious lesions are often observed microscopically or radiographically in locations that are not visible to the naked eye (Hillson, 2000). Teeth with severely worn enamel may also obscure carious lesions. Teeth with severely worn enamel were nonetheless scored for carious lesions because this process is not specific to enamel and is often observed on the roots of teeth (Hillson, 2000). Overall, however, this study acknowledges that it reports a minimal estimation of caries prevalence.

Correlations between tooth attrition and dental caries prevalence are observed among prehistoric people, where lower tooth attrition levels are associated with greater

carious tooth frequencies (Powell, 1985). However, comparatively increased frequencies of carious lesions are observed among skeletal samples with remarkable attrition in prehistoric Japan (Turner, 1979; Temple, 2006). These findings indicate that the relationship between tooth wear and dental caries prevalence is not causal (see also reviews by Hillson, 1996; Larsen, 1997). Yayoi period people from Southern Honshu have greater tooth attrition than those from Northern Kyushu, yet greater frequencies of carious teeth (Todaka et al., 2003). Similarly, greater tooth attrition is observed among the prehistoric foragers from the Jomon compared to the Yayoi period people from Tanegashima Island, yet foragers from the Jomon period have greater caries prevalence (Todaka et al., 2003). These findings suggest that tooth attrition, while different between dietary groups, was not a significant contributor to variation in dental caries prevalence between the groups under study.

Dental caries is an age-progressive process more frequently involving individuals in older age classes because tooth enamel is exposed to acidogenic waste of oral bacteria for longer periods of time (Hillson, 2000, 2001). Age specific comparisons in carious tooth prevalence were, therefore, performed. Following the research of Oyamada et al. (1996), two age groups were used to compare carious tooth frequencies: one group that includes both subadults (age $<$ 15 years) and young adults (15 years $<$ age $<$ 23 years), and an older adult group that includes individuals greater than 23 years. First molar wear was scored in each quadrant of each first molar according to the standards described by Scott (1979). Cumulative scores for each first molar were compared with clavicular fusion, tooth eruption, or pubic symphysis and auricular surface morphology; these features were scored according to standard protocols (Buikstra and Ubelaker, 1994).

Additionally, carious lesions involve molars more often than the anterior dentition or premolars (Arens, 1999). These factors create the possibility for biased results when attempting to reconstruct prehistoric dietary behaviors. For example, greater carious tooth frequencies in a group may reflect an inordinate number of molars. To avoid this bias, percentages of available teeth are compared to ensure that overall carious tooth frequencies reflect dietary variation rather than elevated numbers of teeth with a greater or lesser risk of developing carious lesions. Where dissimilar percentages of teeth are found, the frequency of teeth within a tooth class (i.e., anterior, premolar, and molar) as well as carious tooth frequencies are transformed to reflect the expected distribution of teeth for a sample. Here, anterior teeth should comprise 37.5% of the dentition, while premolars and molars should contribute 25 and 37.5% respectively to the dental arcade (Hillson, 1996).

The caries correction factor attempts to understand carious tooth frequencies in samples where antemortem tooth loss may bias gross estimates of caries prevalence (Lukacs, 1995). This procedure was not used because of the culturally induced patterns of tooth ablation observed among many Yayoi and Jomon skeletal collections (see Harunari, 1986; Nakahashi, 1999; Funahashi and Tanaka, 2004; Temple and Sciulli, 2005).

Between sex differences in caries prevalence is also explored by this study. Biological sex was determined by visually recording morphological features of the Os pubis, greater sciatic notch, preauricular sulcus, and cranium according to referenced standards (i.e., Buikstra and Ubelaker, 1994). The male and female groups were further divided into age groups using methods described earlier. Frequencies of teeth in the anterior, premolar, and molar group were calculated to explain any variation in tooth representation that could bias carious lesion frequencies (see earlier). Frequencies of carious teeth were then calculated for males and females in each age group by dividing the total number of carious teeth per tooth group by the total number of teeth in each tooth group.

TABLE 2. Overall frequencies of carious teeth observed among the Yayoi and Jomon samples

Site	Period	N Teeth	Carious (%)
Doigahama	Early to Middle Yayoi	1417	17.3
Koura	Middle to Late Yayoi	487	14.1
Kanenokuma	Middle Yayoi	1006	11.6
Nagaoka	Middle Yayoi	328	12.8
Torinominae	Middle to Late Yayoi	331	5.7
Hirota	Middle to Late Yayoi	1009	11.0
Hobi	Final Jomon	416	9.4
Inariyama	Late to Final Jomon	330	5.4
Nakazuma	Late Jomon	615	11.2
Tsukumo	Late to Final Jomon	675	9.4
Yosekura	Late Jomon	204	8.8
Yoshigo	Late to Final Jomon	1170	13.2

Differences in carious tooth frequencies were evaluated using a G-statistic. The G-statistic is a more conservative version of the χ^2 test, assessing the independence of nominal data (Sokal and Rohlf, 1981). The G-statistic compares the goodness-of-fit of observed cell frequencies to expected cell frequencies. Here, the G-statistic is used to help explain significant differences in carious tooth frequencies among and between various Yayoi and Jomon dental samples, or more simply, if the presence or absence of carious teeth occurs independently of the temporal periods or geographic locations of sites.

RESULTS

Overall percentages of carious teeth are listed in Table 2. The frequencies of carious teeth listed in Table 2 represent percentages that were calculated without regard to age or sex groups. They are, therefore, not incorporated into the statistical analysis of carious tooth frequency because the results are likely biased by age and tooth attrition rates (Hillson, 2001). Observed frequencies of teeth in each tooth class are listed in Table 3. Table 4 reports the total number of teeth and carious tooth frequencies of individuals with teeth available to score for attrition and control for age. The total number of teeth and carious tooth frequencies observed when Table 2 is compared with Table 4 are unequal. This inequality exists because Table 2 represents every tooth available from the samples, whereas Table 4 represents an estimate of caries prevalence based on age groups and expected distributions of tooth types. Tables 2 and 3 are included to help explain the full sample sizes from which data were collected and to provide interested readers with a source of comparative data.

Percentages of observed tooth types among the Yayoi period samples were approximately equal to those of a normally distributed sample (Table 3). Percentages of observed tooth types among the Late to Final Jomon period were significantly different than the expected distri-

TABLE 3. Age based distributions of teeth by tooth class[a]

	Ant N[b]	Ant (%)[c]	Pre N	Pre (%)	Mol N	Mol %	Σ Teeth
Age Group 1							
Southern Honshu	66	33	56	28	78	39	200
Northern Kyushu	43	35.5	35	28.9	43	35.5	121
Tanegashima Island	40	33.6	29	24.3	50	42	119
Late to Final Jomon[d]	77	18.0	134	31.3	216	50.5	427
Age Group 2							
Southern Honshu	334	36.8	269	29.6	300	33.6	903
Northern Kyushu	279	34.6	225	27.5	318	37.9	822
Tanegashima Island	282	32.7	245	28.5	327	38.8	854
Late to Final Jomon[d]	294	18.2	558	34.6	759	47.11	1611

[a] Only individuals with an estimated age are included in this table.
[b] Number of teeth in a tooth class.
[c] Percentage of teeth in a tooth class.
[d] Observed number of Jomon teeth.

TABLE 4. Age based frequencies of carious teeth by tooth class[a]

	Ant N[b]	C[c] (%)	Pre N[d]	C (%)	Mol N[e]	C (%)	N Teeth	C (%)
Age group 1								
Southern Honshu Yayoi	66	3.0	56	5.3	78	20.5	200	10.5
Northern Kyushu Yayoi	43	2.3	35	–	43	13.9	121	5.8
Tanegashima Yayoi	40	–	29	–	50	10.0	119	4.2
Late to Final Jomon[f]	160.1	1.3	106.8	5.2	160.1	18.8	427	6.5
Age Group 2								
Southern Honshu Yayoi	334	4.8	269	6.3	300	28.6	903	13.2
Northern Kyushu Yayoi	279	9.3	225	3.6	318	10.1	822	8.0
Tanegashima Yayoi	282	0.07	245	4.4	327	18.3	854	8.3
Late to Final Jomon[f]	604.2	3.1	402.8	3.4	604.2	14.1	1611.2	9.8

[a] Only individuals for whom age could be estimated are included in this table.
[b] Number of anterior teeth.
[c] Percentage of carious teeth.
[d] Number of premolar teeth.
[e] Number of molar teeth.
[f] Sample includes the expected frequency of teeth and carious teeth.

bution ($P \leq 0.001$ for all three tooth classes) (Table 3). Expected frequencies of teeth and carious teeth were calculated for the Late to Final Jomon period sample. Expected distributions for tooth classes and carious teeth were produced in each age group by first identifying the expected proportion of teeth for each tooth class. Anterior teeth comprise 37.5% of all teeth in the oral cavity, while 25% of teeth are premolars and 37.5% are molars (Hillson, 1996). Expected tooth distributions were then produced for the Late to Final Jomon period sample by multiplying the total number of teeth within each age class of each temporal group by the expected percentage of teeth in each tooth class: $E_t = N_t\ (P_{ht})$, where E_t is the expected number of teeth in each tooth class, N_t is the total number of teeth within a given age group of each temporal class and P_{ht} is the expected percentage of teeth in each tooth class. Expected numbers of carious teeth were then derived as follows: $E_{nc} = E_t\ (P_c)$, where E_{nc} is the expected number of carious teeth and P_c is the observed percentage of carious teeth. Expected frequencies of carious teeth were then calculated as $E_{pc} = E_{nc}/E_t$, where E_{pc} is the expected frequency of carious teeth. The results are listed in Table 4.

Yayoi period people from Southern Honshu in age Group 1 had significantly greater carious tooth frequencies than Jomon period people ($P \leq 0.05$; df = 1) (Table 4). The Northern Kyushu and Tanegashima Island people from the Yayoi period in age Group 1 did not have statistically significantly different frequencies of carious teeth when compared to foragers from the Jomon period. Southern Honshu people from the Yayoi period in age Group 1 had statistically significantly greater carious tooth frequencies than those from Tanegashima Island ($P \leq 0.05$; df = 1) and Northern Kyushu ($P \leq 0.05$; df = 1) (Table 4). Yayoi period people from Tanegashima Island and Northern Kyushu in age Group 1 did not have statistically significant differences in carious tooth frequencies from one another (Table 4). These results partially support the hypotheses of this study because greater frequencies of carious teeth are observed among one Yayoi period sample (Southern Honshu) compared with those from the Jomon period. Statistically significant differences in carious tooth frequencies between agriculturalists from Southern Honshu compared to those from Northern Kyushu and Tanegashima Island also support the hypotheses of this study by illustrating variation in carious tooth frequencies among Yayoi period groups. Similar frequencies of carious teeth are; however, observed between the people of the Yayoi period from Tanegashima Island and foragers from the Jomon period.

Yayoi period people from Southern Honshu in age Group 2 had significantly greater carious tooth frequencies than the Jomon ($P \leq 0.01$; df = 1) (Table 4). Statistically significant differences in carious tooth frequencies between the Northern Kyushu and Tanegashima Island

TABLE 5. Sex specific variation in caries prevalence by region and age groups[a]

	Ant N[b]	C[c] (%)	Pre N	C (%)	Mol N	C (%)	N Teeth	C[d] (%)
Age Group 1								
Southern Honshu Males	22	–	24	8.3	34	23.5	80	12.5
Southern Honshu Females	22	–	16	–	27	25.9	65	10.8
Northern Kyushu Males	61	–	42	–	63	11.1	166	4.2
Northern Kyushu Females	20	–	12	8.3	14	–	46	2.3
Tanegashima Island Males	42	–	30	–	41	–	113	9.7
Tanegashima Island Females	0	–	0	–	–	–	–	–
Total Yayoi Males	125	–	96	2.1	138	10.9	359	7.8
Total Yayoi Females	69	–	50	2.0	70	10.0	189	6.9
Age Group 2								
Southern Honshu Males	156	3.8	124	4.0	146	18.5	426	8.9
Southern Honshu Females	128	7.8	106	9.4	108	35.1	342	17.0
Northern Kyushu Males	58	5.2	37	10.8	43	16.3	138	10.1
Northern Kyushu Females	33	6.1	18	16.7	16	31.3	67	14.9
Tanegashima Island Males	49	–	40	1.6	46	19.2	135	3.7
Tanegashima Island Females	27	–	22	7.1	29	17.6	78	6.4
Total Yayoi Males	263	3.4	201	5.0	235	18.3	699	8.2
Total Yayoi Females	161	7.5	124	12.1	124	38.7	409	16.6

[a] This table only includes individuals where age was estimated and sex was determined.
[b] Number of teeth in a tooth group.
[c] Percentage of carious teeth in tooth group.
[d] Overall percentage of carious lesions.

people from the Yayoi period compared to foragers from the Jomon period were not observed in age Group 2. Southern Honshu people from the Yayoi period had statistically significantly greater frequencies of carious teeth when compared to those from Northern Kyushu ($P \leq 0.01$; df = 1) and Tanegashima Island ($P \leq 0.001$; df = 1) in age Group 2. The greater frequency of carious teeth observed among the Yayoi period people from Southern Honshu compared with those from the Jomon period supports the hypotheses of this paper, where agricultural samples are expected to have greater carious tooth frequencies than the foraging groups. Variation in carious tooth frequencies observed among the Yayoi period people from various geographic locations in this age group further support the hypotheses of this study. However, the lack of variation in frequencies of carious teeth observed between the Northern Kyushu and Tanegashima Island people in age Group 2 from the Yayoi period compared to those from the Jomon period was unexpected.

Total carious tooth frequencies did not differ between males and females from the Yayoi period in age Group 1 (Table 5). The total frequency of carious teeth among females from the Yayoi period was; however, statistically significantly ($P \leq 0.001$) greater than males in age Group 2. Another way to interpret this table is that total frequencies of carious teeth decline with age among males, while total carious tooth frequencies increase with age among females.

Site specific variation in caries prevalence between the sexes among agriculturalists from the Yayoi period is listed in Table 5. Statistically significant differences in sex specific variation in caries prevalence are not observed between males and females from any region in age Group 1. No statistically significant differences in total carious tooth frequencies are observed between males and females from age Group 2 in Northern Kyushu or Tanegashima Island. However, statistically significant differences in sex based caries prevalence are observed between males and females from Southern Honshu in age Group 2 ($P \leq 0.001$; df = 1). This suggests that the between sex differences in carious tooth prevalence observed among the agriculturalists from Southern Honshu contributed the most to the overall variation in carious tooth frequencies observed among the general Yayoi period samples listed in Table 5. The overall results support the hypotheses of this study by illustrating a greater frequency of carious teeth among the females compared to males of age Group 2 in the Yayoi period, particularly those from Southern Honshu.

DISCUSSION

Evidence for dietary variation during the Yayoi period

The greater frequency of carious teeth among Southern Honshu people compared to those from Northern Kyushu and Tanegashima Island is worthy of note. As is the similar frequencies of carious teeth observed between Jomon period foragers and Northern Kyushu and Tanegashima Island agriculturalists from the Yayoi period. Wet rice and millet agriculture is not associated with increases in carious teeth (Oxenham, 2000; Tayles et al., 2000; Domett, 2001; Oxenham et al., 2002; Pechenkina et al., 2002; Pietrusewsky and Douglas, 2002a,b). Elevated carious tooth frequencies among Southern Honshu agriculturalists are also inconsistent with studies of living populations in Thailand that found decreased carious tooth frequencies among rural children who consumed rice as a primary food source compared with urban children who consumed a broader more sucrose rich diet (Kedjarune et al., 1997). These findings do not, however, indicate that rice lacks cariogenecity.

The sucrose component of rice is negligible, while the clearance time for rice is faster than other cereal products (Sreenby, 1983). Rice is a starch heavy food. Starchy tubers and roots are implicated in elevated carious lesion

frequencies in prehistoric California and Japan (Turner, 1979; Walker and Erlandson, 1986). Starch is, however, a comparatively less cariogenic carbohydrate than sucrose because sucrose is more easily fermented by oral flora (Lingström et al., 1989). These findings may help explain why the transition from economic systems that included the consumption of starchy tubers to those dependent on wet rice were not occasioned by the increased caries prevalence reported during the transition to agriculture in other regions of the globe (Larsen, 1997).

The consumption of heavy starch foods is associated with a cariogenic oral environment because starch adheres food particles to the dentition resulting in a greater clearance time (Firestone et al., 1982). Plaque molecules are then able to attract waste-producing cariogenic flora over an extended period of time. These findings indicate that rice is a cariogenic food product (contra Tayles et al., 2000) and that the consumption of rice and other starch heavy foods in different amounts likely contributed to the variation in caries prevalence between Yayoi period agriculturalists from different regions.

The similar frequency of carious teeth between the people from the Jomon period and those from Yayoi period Tanegashima Island may represent continuity between the two groups. Tooth size variation among living Japanese on Tanegashima Island suggest that the residents of this region are more closely related to Jomon period foragers than modern Japanese from Kyushu and Honshu (Suzuki, 1992). These findings are supported by dental metric and nonmetric variation that indicates close relationships between the Yayoi period people from Tanegashima Island, Amami-Okinawa, and Jomon period foragers (Matsumara, 1995). Behavioral correlates between Jomon and coastal Yayoi period people are also reported. For example, Jomon style harpoons, fishing hooks, and bones of various fish were recovered from the Miura Caves in Tokyo Bay; characteristic Yayoi period rice fields are found atop the embankment overlooking these cave systems indicating that the people of the Yayoi period who occupied this area continued some subsistence strategies associated with the Jomon period (Aikens and Akazawa, 1992).

The greater frequency of carious teeth observed among the Yayoi period farmers from Southern Honshu compared to those from Northern Kyushu likely represents variation in the types of food exploited by these groups. Yayoi period people from Northern Kyushu and Southern Honshu were excavated from coastal regions with similar environmental characteristics. Wet rice paddies from the Early to Middle Yayoi period are reported from both Southern Honshu and Northern Kyushu (Imamura, 1996a). In addition, stable isotope data from these sites suggests that both groups were consuming similar staple foods (Chisholm and Koike, 1999). Surprisingly, Todaka et al., (2003) suggest that the Southern Honshu people from the Yayoi period were likely consuming greater amounts of marine resources than those from Northern Kyushu and that the people from Northern Kyushu likely subsisted on greater amounts of agricultural foods. This claim is made in spite of the greater frequency of carious teeth observed among the Yayoi era people from Southern Honshu (Todaka et al., 2003; this study) and stable isotope studies suggesting similar intake of marine resources between the two groups (Chisholm and Koike, 1999). It is, in fact, more likely that Yayoi period farmers from Southern Honshu consumed greater amounts of cariogenic plant foods than those from Northern Kyushu. The specific dietary choices that contributed to variation in caries prevalence between these two groups are not well understood but probably included wet rice (*Oryza sativa japonica*) and yams (*Dioscorea japonica*) (Crawford, 1992, 2006).

Food boiling and processing increases degradation of starch enzymes and is also associated with an oral environment where the plaque produced by these foods becomes more fermentable by oral bacteria (Lingström et al., 1989). This suggests that variation in the preparation of cariogenic plant foods may also be associated with the differences in carious tooth frequencies between the Northern Kyushu and Southern Honshu Yayoi people given that isotopic evidence indicates similar amounts of plant food consumption between regions.

Of further significance to this study is a greater frequency of malocclusion observed among Yayoi period agriculturalists (Hanihara et al., 1981; Inoue et al., 1986). Malocclusion is associated with greater prevalence of dental caries and other types of oral disease because of the greater clearance time for food trapped between malocluded teeth (Inoue et al., 1983). These findings indicate that the increase in caries prevalence observed among the people from the Yayoi period observed by this and other studies (see Sanui, 1960; Inoue et al., 1986; Todaka et al., 2003) is also partially explained by changes in cranio-facial morphology.

Evidence for agriculture during the Yayoi period

The generally greater frequency of carious teeth among the prehistoric people from the Yayoi period when compared to foragers from the Jomon period is consistent with an agriculturally dependent economy. This finding is supported by a greater degree of social complexity, population density, and archaeological evidence for human reliance on cultigens during the Yayoi period when compared to the Jomon. Agricultural economies have mutually dependent relationships between humans and plants (Rindos, 1984). Changes in plant characters that occur during the domestication process cause the plant to become reliant on human care for survival. Humans then become reliant on the plant to provide a stable source of nutrition. The human component to this mutually dependent relationship is evidenced by increased energy expenditure in the maintenance of plant fields and increased consumption of staple plant resources in concert with increases in population density and sociocultural complexity (Harris, 1989).

Advanced care of plants is observed at Yayoi period sites such as Itatsuke, where evidence for large scale wet rice production and complex farming systems are reported (Imamura, 1996b). Furthermore, increases in population density and social complexity are revealed by studies of demography and burial patterns. These burials include ranked families or clans found in association with one another and particular grave goods (Mizoguchi, 2002, 2003). Clan based hierchies during the Yayoi period suggest a greater degree of social complexity compared to the prehistoric Jomon whose social structure was generally based on lifetime achievements (Temple and Sciulli, 2005). Increased population density is reported in western Japan during the Yayoi period (Koyama, 1978; Hanihara, 1987). Human dependence on

an agricultural product is also supported by carious tooth frequencies among the Yayoi period people from Southern Honshu, where greater caries prevalence indicates increased consumption of cariogenic plant food. Other Yayoi period groups, where significantly increased caries prevalence is not observed, were agriculturalists who consumed less cariogenic food.

Studies of elevated carious tooth frequencies suggest that Jomon period foragers were agriculturally dependent on starchy roots and tubers (Turner, 1979). Paleoethnobotanical evidence for yam cultivation is reported from one Jomon period site (Habu, 2004; Matsui and Kanehara, 2006). Evidence for the types of energy expenditure consistent with human dependence on domesticated products (Rindos, 1984; Harris, 1989) is not observed among prehistoric foragers from the Jomon period (Tsude, 2001; Imamura, 1996a,b; Habu, 2004; Matsui and Kanehara, 2006). Instead, foragers from the Jomon period are more accurately classified as low-level food producers. Low-level food producers rely on domesticates for 30–50% of their annual caloric intake; this schematic is further divided into food producers with and without domesticates (Smith, 2001). The prehistoric Jomon domesticated wild plants and consumed significant amounts of domesticated and wild plants as well as wild game (Imamura, 1996a,b; Habu, 2004). The extent to which domesticated products contributed to the Jomon diet is, however, unknown as is the amount of energy expended by the Jomon on the care of domesticated plants (Tsude, 2001). In addition, the level of social structure necessary to organize people into various task groups responsible for the care and maintenance of agricultural products was likely absent until the appearance of kin-based leadership during the Yayoi period (Mizoguchi, 2002, 2003).

Differences in male and female dietary behavior

The greater frequency of carious teeth among Yayoi period females from Southern Honshu compared to males in age Group 2 suggests an environment where behavioral variation between the sexes contributed to differences in oral disease. It is also important to note that a lower level of attrition among female teeth may be associated with the greater prevalence of carious teeth (i.e., Powell, 1985). However, studies of dental attrition during the Yayoi period suggest that the differences in tooth wear between males and females were not significant, particularly after 25 years of age (Fujita, 1993). These findings suggest that variation in dental attrition between the sexes is not related to the greater carious tooth frequency observed among females from the Yayoi period in age Group 2.

Increased caries prevalence among women may also be related to the earlier eruption of female teeth. Teeth which erupt at earlier ages are exposed to oral bacteria for extended periods of time and may be at greater risk of developing carious lesions (DePaola et al., 1982). Clinical research has, however, demonstrated that this relationship is weak and that the earlier eruption times of female teeth have little association with greater caries prevalence (Moorrees, 1957). The similar prevalence of caries in age Group 1 between males and females (Table 5) further suggests that the relationship between eruption time and caries prevalence did not contribute to the greater frequency of carious teeth among females from the Yayoi period.

The sexual division of labor in many traditional agricultural and horticultural societies, where men are responsible for hunting and women are more involved with the gathering/care of plants, is associated with differential access to meat and plant products and subsequently observed carious teeth (e.g., Walker and Hewlett, 1990). These differences are also observed in bioarchaeological studies where sex-based variation in carious tooth frequencies are attributed to greater consumption of meat by men and greater plant consumption among women (Larsen, 1983; Kelley, 1991; Larsen et al., 1991; Lukacs and Pal, 1993; Lukacs, 1996). Similar results are reported among agricultural people from select sites in Vietnam and Thailand (Oxenham, 2000; Tayles et al., 2000).

The lack of variation in caries prevalence between the sexes among the Northern Kyushu sample from the Yayoi period is similar to the findings of Oyamada et al. (1996), who report little sex specific variation in carious tooth prevalence during the Yayoi period from different sites in the same region. These findings indicate that sex specific variation in diet was likely practiced among the Yayoi period people from Southern Honshu, where carious tooth frequencies and stable isotope analysis (see later) suggest sex specific differences in the types of foods consumed. Yayoi period farmers from Northern Kyushu likely had little variation in diet between males and females.

It is, however, important to note that recent studies report a correlation with female hormones and dental caries (Lukacs and Largaespada, 2006). Increases in estrogen secretions during menstruation, puberty, and pregnancy are associated with a reduction in salivary flow rates in females. Normal or increased salivary flow rates maintain a critical oral pH; fewer species of bacteria are able to ferment foodstuffs once an optimal pH balance is achieved (Arens, 1999). Increases in hormone levels during pregnancy are also associated with increased carious tooth frequencies in women (Lukacs and Largaespada, 2006). Pregnant women are, for example, found to have modified saliva with reduced buffer capacity and other factors that promote oral bacteria growth and reproduction. A clinical comparison of *Streptococcus* levels in pregnant and nonpregnant women revealed a significantly greater level of oral bacteria in the pregnant group, possibly associated with a reduction in salivary flow rate and buffer capacity (Lukacs and Largaespada, 2006).

These findings carry important potential for the interpretation of dental caries prevalence in prehistoric people and must be considered as a possible contributor to the differences in dental caries prevalence between Yayoi period males and females. However, dental caries prevalence among prehistoric foragers from the Georgia Bight region of the southeastern United States has little variation between males and females (Larsen, 1983). In addition, the prehistoric foraging site of Non Nok Tha in Thailand has no significant sex based differences in carious tooth prevalence (Douglas, 2006). Populations with little differentiation in the sexual division of labor such as South American horticulturalists and Australian Aborigines also have little variation in carious tooth frequencies between the sexes (Campbell, 1938; Walker et al., 1998). It is expected that a more universal trend of elevated carious tooth frequencies would be observed among females if hormone fluctuations were associated with increased dental caries prevalence.

A review of demographic trends in cemeteries among prehistoric people from Europe, North Africa, and North America suggests an increase in birth rate following the transition to agriculture in multiple regions of the globe (Bocquet-Appel and Naji, 2006).

Greater birth rates among prehistoric farmers imply a greater number of pregnancies. The increase in birth rate observed among prehistoric farming societies may, therefore, be associated with a spike in the hormones that foster greater oral bacteria counts during pregnancy and possibly contribute to increased caries prevalence among females from agricultural societies (Lukacs, no date). Population spikes are reported in Yayoi era Northern Kyushu and Southern Honshu (Koyama, 1978) and may be associated with increased birth rate (Imamura, 1996a).

It is hypothesized that the rate at which agricultural products are adopted is associated with variation in caries prevalence by sex; primary locations for agricultural adoption will have lower sex-based dietary differences and fertility as well as lower sex-based variation in caries prevalence, while peripheral regions where agriculture more gradually diffused will have greater between sex variation in carious tooth frequencies associated with fertility increases and sex-based dietary variation (Lukacs, in press). This hypothesis is based on observations in the Levant, where gradual increases in caries prevalence are observed in regions where agriculture was first introduced (Eshed et al., 2006).

Core locations for the earliest rice agriculture are the Yangtze River Valley and the northern Henan province of China dating to ~10000 BP; the earliest evidence for wet rice farming is reported from the Caoxesian site also located along the Yangtze River and dated to ~4500 BP as well as the adjacent ecological zones of Korea dating to ~5500 through 4000 BP (Crawford, 2006). Bioarchaeological studies of sex variation in oral health and demography have not been undertaken in the Yangtze River Valley or Korea. Sex based differences in carious tooth frequencies are, however, observed at some, but not all, early agricultural sites in Thailand and Vietnam, two regions where wet rice agriculture spread from the Yangtze River Valley (Oxenham, 2000; Tayles et al., 2001). General increases in fertility are also reported in these areas (Oxenham, 2000; Pietrusewsky and Douglas, 2002a,b) indicating a variable link between fertility increase and sex based variation in caries prevalence for Southeast Asia.

Wet rice agriculture also spread from the Asian continent to Japan (Imamura, 1996a,b; Tsude, 2001). An absence of differences in carious tooth frequencies between males and females from Northern Kyushu and presence of differences in carious tooth frequencies between males and females from Southern Honshu is observed (Table 5). These results also partially support the hypothesis that carious tooth differences between males and females along with fertility are accentuated in peripheral agricultural zones. It remains necessary to further investigate demographic trends in peripheral centers of wet rice agriculture that lack sex based differences in carious tooth frequencies such as Northern Kyushu. Similarly, studies of both fertility and sex based differences in caries prevalence between the sexes remain important components to better understanding the impact of wet rice agriculture and birth rate on oral health in core regions of wet rice agriculture.

Stable isotope studies of Yayoi period skeletal remains from the Koura site found evidence for greater consumption of marine products by males, while females consumed greater amounts of terrestrial plant foods (Chisholm et al., 1992). The age and sex specific sample sizes from the Koura site were too small to contribute meaningful data to a by sex analysis of carious teeth. However, Koura is located in Southern Honshu (Fig. 1). Yayoi period dental samples with statistically significantly greater carious teeth among females compared to males were recorded from several sites in Southern Honshu (Table 5). The combination of caries prevalence and isotopic evidence for dietary variation between the sexes suggests that diet was the primary contributor to the sex-based differences in carious tooth frequencies observed among the Yayoi period people from Southern Honshu.

CONCLUSIONS

Patterns of dietary and behavioral variation are demonstrated among Yayoi period people, where the transition to agriculture precipitated increases in carious tooth frequencies as well as variation in carious tooth frequencies between geographic locations and the sexes. Here, this study finds agreement with other reports documenting evidence for greater carious tooth frequencies among Yayoi period farmers from Southern Honshu compared with Jomon period foragers (Sanui, 1960; Inoue et al., 1986; Todaka et al., 2003) indicating a dietary change during the transition to agriculture and possibly difficulties associated with increased malocclusion. This study also found evidence for variation in the frequency of carious teeth between Yayoi period sites indicating that the dietary choices of prehistoric Japanese agriculturalists were variable.

Variation in carious tooth frequencies in age Group 2 between Yayoi period males and females from Southern Honshu is observed; a greater prevalence of dental caries is observed in the female group. The greater prevalence of dental caries among these females is attributed to dietary differences between the sexes. Stable isotope studies of Yayoi period farmers suggest a sex-specific breakdown in food consumption with males consuming greater amounts of marine resources and females consuming more plant based products, specifically in Southern Honshu (Chisholm et al., 1992).

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