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その他のタイトル	歯髄腔容積を用いてベイズ法により推定した縄文時代人の平均余命
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論文の内容の要旨

LIFE EXPECTANCY OF JOMON PEOPLE ESTIMATED FROM THE DENTAL PULP VOLUMES BY BAYESIAN APPROACH

（歯髄腔容積を用いてベイズ法により推定した縄文時代人の平均余命）

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The Jomon period is one of the Japanese prehistoric periods which began about 13,000 years BP and lasted roughly 10,000 years thereafter. Human life span (longevity) during the Jomon period is interesting when compared with those of the succeeding periods, which enables to shed light on the substantial change in ecology, subsistence and society over the human population history of Japan. In broader perspectives, it is also interesting as it provides an insight into the evolution of human life history which distinguishes humans from the other primates. The longevity of Jomon people has been previously estimated from the skeletons by Kobayashi (1967) where it was represented by the life expectancy at age 15. The result was 16.1 years for males and 16.3 years for females. However, the age estimation method he employed included a statistical problem. Assignment of age to the skeleton referring to known ages of skeletons with similar aging expression is classified as inverse regression in statistical terms. It has been pointed out that the age estimation by inverse regression is to be influenced by the age distribution of the reference sample, and the reconstructed age distribution is to mimic that of the reference sample (Bocquet-Appel and Masset, 1982). Since the reference sample by Kobayashi (1967) was composed dominantly of young adult individuals, a number of Jomon ages should have been underestimated in his study.

To circumvent the problem, I adopted Bayesian approaches. Bayesian approaches use reference sample to derive the probability to obtain an expression of the age indicator for an individual of

certain age. This is classified as forward regression, and not influenced by the age distribution of the reference sample.

Furthermore, another problem might have distorted the estimation by Kobayashi (1967). Different durability of bones against taphonomic processes presumably filters out the fragile old skeletons. This could make the estimation of ancient mortality distribution younger than the reality because the skeletons observed by researchers would under-represent the deaths of the old individuals. While bones are likely differentially preserved because the remodeling activity declines throughout the life, teeth are less likely on this regard because remodeling does not occur in teeth. To minimize the effect of differential preservation, I used teeth as the age indicator for Jomon skeletons.

The pulp cavity in teeth reduces with age due to dentin apposition on the pulp wall through the life. I utilized the pulp volume ratio (PVRrt: volume proportion of the pulp cavity in the root portion) as the age indicator. Those volumes were measured on the digital imageries obtained by microfocus computed tomography (micro-CT). I scanned 363 recent-modern Japanese lower canines and established a statistical model to describe the probability distribution of PVRrt at a certain age. Lower canines were exclusively used to reduce undesired biases in the reduction pattern caused by the morphological variations.

Next, the PVRrt values were obtained from 234 Jomon individuals stored in The University Museum, The University of Tokyo (UMUT). As in Kobayashi (1967), the observations were limited to those individuals considered at or above age 15. Sexes were not separated in this study to avoid too much statistical assumptions in the Bayesian approach.

Bayesian approaches update the probability (called prior probability) of the subject to new one (called posterior probability) by applying the information from observations. The information (called likelihood) is the probability to obtain the observations when a certain hypothesis about the subject is assumed. In this dissertation, 5 parameters (α, β, γ, λ, θ) describe the subject, among which α and β describe the age-at-death distribution of Jomon people. The prior probability of the parameters (α, β, γ, λ, θ)=Ω can be updated by the likelihood to the posterior probability as

$$p(\Omega \mid z_1,\ldots,z_{234}) = \frac{g(\Omega)\cdot L(\Omega)}{\int_\Omega g(\Omega)\cdot L(\Omega)\cdot d\Omega},$$

where $z_1,\ldots,z_{234}$ are the observations on 234 Jomon individuals, $g(\Omega)$ is the prior probability function, and $L(\Omega)$ is the likelihood function on the observations $z_1,\ldots,z_{234}$. Here, I explain what those 5 parameters stand for while explaining the components of the likelihood function. The start point for the likelihood calculation is to formulate the probability (density) for an individual i to be at age x *and* have an expression z_i. This probability was computed by multiplications of the following four probabilities:

(1). $p(x \mid \alpha,\beta)$: the probability density for the individual (with lower canine) to be at age x.

(2). $p(\text{PVRrt} \mid x, \gamma)$: the probability density distribution of PVRrt value at age x, parameterized by using the recent-modern Japanese samples. The parameter γ represents the rate of PVRrt reduction, which could be different in Jomon people from that of recent-modern Japanese and thus was set as one of the target to give the posterior probability distribution by the Bayesian approach.

(3). $p(\text{epiphyseal state} \mid x)$: the age-conditional probability of the state of epiphyseal closure at sternal end of the clavicle. It was either "complete" or "incomplete." This additional age information was necessary to compensate for the unknown PVRrt reduction rate γ for Jomon people. This probability was set as 1 when clavicles were not preserved for the individual.

(4). $p(\text{clavicle preservation} \mid x, \lambda, \theta)$: the age-conditional probability for the individual with lower canine to preserve the clavicle for the epiphyseal observation. The parameters λ and θ describe the change in the probability with age, and the posterior probability distributions were given to them by the Bayesian approach.

The observation z_i denotes the set of (2)–(4) observations. Integrating the multiplication of the four probabilities for whole age range gives the probability to have the observation z_i for the individual i. The likelihood function was composed of multiplication of this probability for the 234 Jomon individuals.

Before conducting the Bayesian approach, the maximum likelihood estimation was calculated for the life expectancy of Jomon people at age 15 (e_{15}), to compare the estimation with that by Kobayashi (1967). The maximum likelihood is the method to seek the parameter set which maximizes the likelihood function. The life expectancy at 15 calculated from the maximum likelihood estimate was 30.6 years. To compare this result with that of Kobayashi (1967), pseudo-estimations of e_{15} were calculated from 234 pseudo-samples generated computationally upon the null hypothesis that the age-at-death distribution in Kobayashi (1967) was true. While the set of pseudo-samples were generated 500 times, the estimation from the real Jomon samples was larger than all the pseudo-estimations, indicating the real Jomon samples used in this study is significantly older than the age-at-death distribution estimated by Kobayashi (1967).

The prior probability is that for the five parameters (α, β, γ, λ, θ) *before* obtaining the observations. I suppose that the ideal prior is the distribution of the parameters hypothetically achieved by a number of human populations with similar genetic compositions and similar environments to those of Jomon people. Since such information is not available, I used uniform prior distributions. However, some prior information about the parameters for age-at-death distribution (α, β) could be obtained from modern and historical human life tables. A scatter diagram of the life expectancy at age 15 (e_{15}) and the coefficient of variation of the years-to-death after age 15 (CV) indicated a human specific tendency for their survival profiles, which was distinct from that of other primates. This tendency enabled a non-uniform prior probability distribution for α and β. From the human distribution on the diagram, the non-uniform prior for α and β was calculated. This prior should be closer to the ideal one than is the uniform prior.

The posterior probability distribution was calculated from the above-mentioned prior probability distributions and the likelihood function. When uniform priors were used for all the parameters, the 95% credible interval (defined as the interval between 2.5 percentile and 97.5 percentile values of the posterior probability) of the life expectancy at age 15 was 17.8–41.8 years. The mean value was 26.8 years. When the non-uniform prior was applied to α and β and uniform priors to the rest, the 95% credible interval was 29.2–41.5 years. The mean was 35.2 years.

As the conclusion, the life expectancy for Jomon people at age 15 was substantially older than that estimated by Kobayashi (1967). The possible range is 17.8–41.8 years. From the mean values by the two prior assumptions, I suppose that 27–35 years is the most probable range of the expected years for Jomon people at age 15.