Estimating the Age Structure of a Buried Adult Population: A New Statistical Approach Applied to Archaeological Digs in France

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KEY WORDS paleodemography; age estimation; Bayesian methods; mortality distributions; Dirichlet

ABSTRACT Paleodemographers have developed several methods for estimating the age structure of historical populations in absence of civil registration data. Starting from biological indicators alone, they use a reference population of known sex and age to assess the conditional distribution of the biological indicator given age. However, the small amount of data available and the unstable nature of the related statistical problem mean that most methods are disappointing. Using the most reliable reference data possible, we propose a simple statistical method, integrating the maximum amount of information included in the actual data, which quite significantly improves age estimates for a buried population. Here the method is applied to a French cemetery used from Late Antiquity to the end of the Early Middle Ages. Am J Phys Anthropol 000:000–000, 2012. ©2012 Wiley Periodicals, Inc.

Age is a fundamental concept in demography, but cannot be directly measured for most population groups in the past, especially those for whom there are only skeletal remains. When age at death is estimated from biological indicators, such as growth for immature subjects or ageing for adults, we are inevitably faced with a major statistical problem due to the lack of a direct relationship between data from bone and teeth remains and the subject's chronological age. At best we only have a statistical correlation, unfortunately a weak one and all the more puzzling as the measurements often concern small numbers of skeletons in the archaeological population and, to some extent, in the reference population.

Although the stage in a child's growth at which they died can be established (by observing dental mineralization or measuring the long bones) and their age deduced with satisfactory accuracy, the criteria of biological ageing, all that is available for estimating an adult's age at death, vary widely from one individual to another and raise specific problems, which this article addresses.

GENERAL FRAMEWORK

All estimates of age are based on the observation of one or more biological indicators of age available from most skeletons. Various indicators have been proposed, such as changes in the pubic symphyseal face or the iliac auricular surface, development of teeth or osteoporosis, or synostosis of the cranial sutures. However, none of the age indicators used for adults correlates in a satisfactory statistical manner with biological age (Masset, 1982; Bocquet-Appel and Masset, 1982; Séguy and Buchet, 2011), especially where there are problems of differential preservation because hip bones, say, are more fragile than others. The development of cranial suture closure was one of the earliest indicators used to estimate age at death (Broca, 1875) and it is still used. Speed of measurement and low variability between observers makes it preferable to other age indicators; besides, its statistical correlation with recorded age is not worse than any other biological age indicator. If cranial sutures are too imprecise to be of practical use in forensic research (to access an age to one dead person), they are suitable for archaeological data, where the goal is to estimate age at death distribution for all buried people. We followed Claude Masset's method (1982, 1989) in reading the degree of suture closure, but we grouped the observations in five stages of synostosis, as defined in the *Manuel de paleodemographie* (Séguy and Buchet, 2011). We also used Claude Masset's reference population, suitably corrected and completed (*ibid*).

Paleodemographers have long sought methods to narrow the often wide range of uncertainty attached to the estimation of age at death for a sample of skeletons for which one or more biological indicators are observed. A useful summary may be found in Séguy and Buchet (2011). Currently accepted principles are those described by Hoppa and Vaupel (2002) in the section entitled "The

Additional Supporting Information may be found in the online version of this article.

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Received 19 June 2012; accepted 10 October 2012

DOI 10.1002/ajpa.22187
Published online in Wiley Online Library (wileyonlinelibrary.com).

TABLE 1. Age distribution in Antibes civil registers

18–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80 and over
0.0309	0.0650	0.0618	0.0537	0.0537	0.0650	0.0520	0.0504	0.0650	0.0927	0.0732	0.1203	0.0927	0.1236
0.0309	0.1268		0.1073		0.1171		0.1154		0.1659		0.2130		0.1236

Rostock Manifesto for paleodemography." They may be summarized in three points:

1. Develop reliable reference collections where both chronological age and biological stage are known for each skeleton and use these data to estimate the probability of observing a suite of skeletal characteristics c at known age a: $\Pr(c \mid a)$;
2. Admit an "invariance hypothesis" supposing that the conditional distribution of stage indicators at a given age is constant over time, at least to a first approximation, making it possible to apply to the target sample the estimates of conditional probabilities made above;
3. Devise a statistical method to estimate as accurately as possible the age structure for a given site using the two points above, data from the site's biological indicators and any other available information or reasonable hypothesis.

These three methodological points warrant a number of comments.

MATERIAL AND HYPOTHESES

Reference collection

All the reference collections currently available contain intrinsic shortcomings that affect the accuracy of the estimates. For example, the fact that the comparison collections comprise only a few hundred individuals makes it impossible to cover the full range of possible results accurately. Furthermore, most of the collections are of people with low socioeconomic levels, which may affect the estimate of age at death, because the development of the accepted biological age criteria is influenced by the population's state of health and socioeconomic class.

The reference population we have used is taken from three osteological collections conserved in Portugal: the Ferraz de Macedo collection in Lisbon, a set of skeletons from the Department of Anthropology of the University of Coimbra (both already used by Claude Masset) and the major collection of skeletons held by the Bocage Museum (National Museum of Natural History) in Lisbon. This collection concerns poor or ill people who died in the hospital, one third of them of tuberculosis. Our population was reconstructed from individuals in these three major collections of 19th and 20th century skeletons, after taking into account the main shortcomings (age heaping, lack of old people, structurally young population, lack of men). The details of the data are given in Séguy and Buchet 2011 (Tables 1–3: 370–372, and in the data and program CD-ROM) and their characteristics are summarized in Supporting Information Tables S4–S6.

Invariance hypothesis

A crucial point is the "invariance hypothesis." It assumes that the conditional distribution of stage indicators at a given age is constant over time, at least to a first approximation. This hypothesis in fact underlies all the estimates made in Hoppa and Vaupel. For example, Love and Müller (2002) state:

"This is a minimal assumption that must be made to analyse the target data. Any assumption that is weaker would make the analysis virtually impossible."

It also underlies most anthropological studies (Howell, 1976; Konigsberg and Frankenberg, 1992; Müller et al., 2002), since all current age estimation methods have been developed from sets of skeletons from recent times (the oldest collections date from the late 19th century).

Paleodemographers are aware of the risks involved in this hypothesis and have given thought to what biases might arise from differences in the growth or ageing processes between the archaeological population and the reference population. The possibility of a drift over centuries in biological age indicators has been debated within the research community for some years (Masset, 1982; Molleson and Cox, 1992, 1993; Bocquet-Appel and Masset, 1995; Hoppa, 2000) with no conclusion.

"*Although the possibility of a drift in biological age indicators over centuries cannot be dismissed, paleodemographers have tended to neglect it because they cannot measure it and have hoped that any variations are not too wide*" (Séguy and Buchet, 2011).

We should not, therefore, place excessive confidence in this hypothesis, but we cannot avoid placing some!

Other hypotheses

In an attempt to improve the effectiveness of the methods for estimating the age structure of a given population, site data (biological indicators), and reference data have been regularly supplemented by various hypotheses about that structure. For example, Hoppa and Vaupel (2002) propose adopting a model of mortality and even suggest that this is essential when they write:

"*While, ultimately, the goal would be to proceed without the need to impose any predefined patterns of mortality, currently the kinds of osteological data available are not adequate to allow for nonparametric approaches, at least for intervals of reasonable length. As a result, there is a need to incorporate parametric models of mortality into paleodemographic reconstructions*" (p. 6).

Similarly, Bocquet-Appel and Bacro (2008) examine a series of 736 mortality models, Gompertz-Makeham distributions, and extreme values discretized to correspond to the number of age groups under consideration, and within this set (or rather within its convex envelope) they seek the best estimate of the mortality of the target population.

This article examines how to escape from excessively strong hypotheses about the age structure to be estimated by introducing a maximum amount of *a priori* quantitative or qualitative information. Use is also made of the concept of "preindustrial mortality standard" (Séguy et al., 2008; Séguy and Buchet, 2011) not as a hypothesis but as a reference point from which the effective mortality of a given site may be evaluated. As neither contemporary life tables nor paleodemographic mortality models can accurately reconstruct the mortality patterns experienced by pre-industrial populations, one of us has developed specific life tables based on a large set of published tables representing mortality before epidemiological transition, concerning diverse times and places. The pre-industrial standard is defined as the mean value of this large number of statistical and prestatistical life tables characterizing the mortality of preindustrial populations. We assume that the demographic behavior of archaeological populations closely resembles that of observed preindustrial populations in "normal" conditions. Life tables are not indeed adequate for studying periods with accidental events (war, starvation, epidemic) which substantially modify probabilities of dying.

MODELING AND STATISTICAL METHOD

Formalizing the problem

Here we address the discrete case most often examined, where a suite of skeletal characteristics are classified into l stages and ages into c classes. The reference population provides data n_{ij}, number of individuals at stage i and age j ($i = 1,\ldots,l$; $j = 1,\ldots,c$). For the target population we have the distribution of bone stages: m individuals observed of whom m_i are at stage i.

We denote by p_{ij} the probability that a randomly selected individual from the target population is at stage i and age class j; the sum over i of the p_{ij} is denoted by p_j (this is the probability that an individual will be of age j); the sum over j of the p_{ij} is denoted by π_i (this is the probability that an individual will be at stage i); the conditional probability of stage i where age j is known is denoted by $p_{i|j}$. These various probabilities are positive and verify the relationships $\sum_i \pi_i = \sum_j p_j = 1$ and $\sum_i p_{i|j} = 1$ for all j. They are also connected by the following relationship:

$$\sum_j p_j p_{i|j} = \pi_i \quad \text{for all } i = 1, \ldots, l \qquad (1)$$

The probabilities p_j are to be estimated, namely the age structure of the target population, by means of the data described above, taking account of the invariance hypothesis. This is therefore apparently a quite standard problem, since the reference data can be used to estimate the probabilities $p_{i|j}$ and the π_i are estimated by $\frac{m_i}{m}$. Replacing these in Eq. (1), one can obtain estimates of the p_j by regression (Courgeau, 2011), perhaps conveniently weighted (note too that the coefficients of the first term are in principle subject to error). One may also use the fact that the distribution of the data can be modeled by multinomial laws; as various authors have pointed out (e.g., Konigsberg and Frankenberg, 2002, and Wood et al., 2002), if one does not allow for the errors in estimating the probabilities $p_{i|j}$, the maximum likelihood method is none other than the IALK algorithm (Kimura and Chikuni, 1987) or, equivalently, the IPFP algorithm or "successive approximations" (Masset, 1982) which remedy some shortcomings of the ALK method (Courgeau, 2011; p. 272–273). One may also consider a convenient probability law for the reference data (Caussinus and Courgeau, 2011). These various approaches provide disappointing results for a number of reasons, of which the major one is the small size of the data available, together with an intrinsic instability since the correlation between stages and ages is relatively low. It is also clear that the model is not identifiable if $c>l$ as has also been pointed out in the literature (e.g., Konigsberg and Frankenberg, 2002).

Other statistical approaches have therefore been proposed, mainly based on introducing mortality models. There are two main ways of proceeding.

a. One can replace the non-parametric problem described above with a parametric model by introducing a model of mortality with a small number of parameters instead of the *l-1* parameters p_j, for example, a Gompertz two-parameter model. This is recommended by Müller et al. (2002) among others. They also estimate the conditional probabilities of the stages for a given age by a kernel method, whereas the estimates made here are done by fixed-window regression, but this is a minor difference. Similarly the "bulk" of the Rostock volume (Hoppa and Vaupel, 2002) is fully parametric. Provided that the hazard models do not include too many parameters (Gompertz two-parameter model, Gompertz-Makeham three-parameter model, Siler five-parameter model, etc.), they can be estimated using the maximum-likelihood method. However, these methods introduce a number of additional hypotheses that we have hardly any means of verifying. They include a stationary or stable population to ensure that the hazard model applies to current conditions; and continuity in the age distribution of a given stage, leading to different distributions according to the methods used. Lastly, the Rostock methods assume that the observed frequencies offer correct estimates of the probabilities.
b. Bocquet-Appel and Bacro (2008), on the other hand, look for a vector of the p_j as a least-squares solution of the linear system Eq. (1) from a set of "candidate" vectors they determine in advance in order to represent a whole range of possible mortality distributions. They also bootstrap the reference data and select a mean of the results obtained from the various repetitions, leading to a final solution within the convex envelope of the candidate vectors. However, since the uncertainty about the site data is not introduced, the confidence intervals proposed are much too optimistic and consequently unusable.

Whatever is sometimes said in the literature, the statistical methods proposed in the past are all frequentist in nature, even if some are dubbed "Bayesian" because of the use of Bayes' formula (a point made by Konigsberg and Frankenberg, 2002; p. 306). We propose rather a Bayesian method in the sense commonly used by statisticians:

- The unknown parameters are assumed to be random with a prior distribution by which one seeks to allow for characteristics known independently of the observed data;
- The probability law of these parameters is calculated conditionally on the observations: this is the posterior distribution on which the statistical inference is based.

A Bayesian statistical approach

The principle of the method is developed by Caussinus and Courgeau (2010). We recapitulate the broad outlines here with emphasis on the points that are crucial for its practical application, particularly the selection of the prior distributions. It is natural to consider that the frequencies m_i (i = 1,. . .,l) are the observed values of a multinomial distribution in which the parameters π_i are related to p_j and $p_{i|j}$ by [1]. We shall use these last two sets of parameters to continue the modeling. According to the Bayesian paradigm, a prior distribution must first be proposed for each one.

For the prior distribution of parameters p_j it is natural to adopt a Dirichlet distribution since it is the conjugate prior for the multinomial (Robert, 2001; Gelman et al., 2003), but care must be taken in examining the parameters for this distribution, say (β_1,. . ., β_c). In the absence of any particular information, a neutral procedure would be to opt for a uniform distribution and take $\beta_j = 1$ for all j. However, other choices are more judicious in this case. Since Séguy et al. have established standard mortality distributions for the preindustrial period (Séguy et al., 2008; Séguy and Buchet, 2011), we may start from that sort of "standard" mortality distribution (male or female if that information is available, otherwise general) and calculate the probabilities for the various age classes. These are then taken to be the means of the prior distribution, which provides the β_j's up to a coefficient of proportionality, e.g., the β_j/β_+ where β_+ is the sum over j = 1,. . .,c of the β_j's. It remains to choose β_+: theoretical and practical considerations (simulations) have shown that a reasonable choice is to make β_+ equal to c (see Caussinus and Courgeau, 2010, 2011). Finally, in some circumstances one may have supplementary information about the specific site leading one to suppose that even without considering the available biological measurements, the specific population has a particular structure: it is useful in such cases to introduce this information via the β_j parameters (an example is given below: Using specific prior information).

The prior distribution G of parameters $p_{i|j}$, i = 1,. . .l and j = 1,. . .c, is provided by the reference data: considering the multinomial character of their distribution and the absence of any other prior information, it has been shown that it was reasonable to take, for each age class j, a Dirichlet distribution with parameters $\alpha_{ij} = n_{ij} + 1$ (i = 1,. . .,l) (Caussinus and Courgeau, 2010, 2011).

Denoting by M the set of frequencies m_i and by P and p, respectively the sets of parameters $p_{i|j}$ and p_j, the joint distribution of (M, P, p) is

$$f(M,P,p) = g(p)G(P)\frac{m!}{\prod_i m_i!}\prod_i\left(\sum_j p_j p_{i|j}\right)^{m_i}$$

The density of the posterior distribution of the p_j parameters is expressed as the ratio of two integrals, like various quantities relating to this distribution (means, variances, co-variances, cumulative distribution functions, etc.). For example, the posterior mean of p_j is:

$$\frac{\iint p_j f(M,P,p)dp\ dP}{\iint f(M,P,p)dp\ dP}$$

All these integrals can be easily evaluated by a Monte Carlo method. In practice, the posterior means can provide point estimates of the probabilities of death for the various age groups; the posterior variances (or standard errors) can be used for an initial evaluation of the accuracy of these estimates but, especially in the frequent case of highly asymmetrical distributions, one should prefer to calculate credible intervals deduced from the cumulative distribution functions (a credible interval is an interval within which an unknown parameter is found with a given probability conditional on the available observations (see Robert, 2001), its use may be likened to that of confidence interval in the frequentist approach). An R script (R Development Core Team, 2011) for computing these various estimates is available on the CD-ROM accompanying the *Manuel de paléodémographie* (Séguy and Buchet, 2011), and may be requested from the authors.

The statistical analysis is wholly based on the posterior distribution of the p_j, which is a revision of the prior distribution after consideration of the archaeological skeletal stages. An important aspect of the results obtained is the manner in which the prior distribution moves toward the posterior one: this makes it possible to evaluate the estimated structure of a site in comparison with the prior structure, usually the "standard" one. Besides the standard errors or any other indicators of precision, this provides useful qualitative information by which one can judge the reliability of the estimates derived from the posterior distribution. Finally, even if the choice of the prior distribution has an influence on the estimated probabilities of death by age classes, it cannot be an artifact if the statistical analysis is done properly: a judicious choice will improve these estimates with the resources for monitoring their quality. This is illustrated in the next two sections.

EFFICIENCY OF THE METHOD

Selection of age classes

We use archaeological and historical modern data from the city of Antibes (southern France, late 19th century) both to compare the Bayesian method with former parametric proposals and to evaluate the best way for age grouping.

Before a new real estate project, a preventive dig[1] uncovered over 200 tombs from the later extension of the former municipal cemetery of Antibes (1877–1897), abandoned a century ago. These tombs contained bodies not claimed by their families when the town council proposed to transfer the remains of those buried in the old cemetery to a new one. Examination of the exhumed skeletons was justified by two paleodemographically interesting features of this population sample: those buried in the cemetery were contemporaries of the reference population we use (see below) and the local demographic data were sufficiently precise to reveal the living population structure and to establish the age distribution of mortality for late 19th century in Antibes. Exceptionally, it then became possible to compare the demographic data, taken from statistical sources contemporary of the cemetery, with the results obtained from the skeletons by paleodemographic methods.

The following statistical analysis covers the 73 skeletons for which a stage of cranial suture closure could be calculated, with the data analyzed for both sexes together because of the large number of skeletons of

[1]Archaeological dig from October to December 1998 by a team from INRAP (Institut national de recherches archéologiques préventives) under Philippe Vidal. The anthropological and demographical analysis was done by two of the authors (Séguy and Buchet, 2011).

TABLE 2. Antibes, 10-year classes, probabilities estimated by various methods

Age classes	18–19	20–29	30–39	40–49	50–59	60–69	70–79	80 and over
Bayes	0.028	0.144	0.119	0.134	0.155	0.187	0.164	0.069
MLG1	0.035	0.168	0.153	0.135	0.117	0.099	0.081	0.212
MLW1	0.045	0.191	0.147	0.115	0.092	0.073	0.059	0.278
MLG2	0.040	0.183	0.154	0.128	0.105	0.086	0.069	0.235
MLW2	0.068	0.227	0.131	0.087	0.062	0.047	0.037	0.340

TABLE 3. Antibes, 10-year classes: Comparison between various estimates and recorded values

	Bayes	MLG1	MLW1	MLG2	MLW2
Sum of squared deviations	0.008	0.034	0.062	0.045	0.107
Maximum deviation	0.055	0.132	0.154	0.144	0.216

indeterminate sex. The frequencies observed for the five stages in the sample are 21, 14, 12, 16, and 10.

Analysis was made successively with 8 and 14 age classes: in both cases the youngest was 18 to 19 and the oldest 80 and over, with intermediate 10-year classes (8 in all) or 5-year classes (14 in all).

The age distribution observed in the records is given in Table 1 (see above).

In addition to earlier comparisons (Caussinus and Courgeau, 2010, 2011), the data were processed using three methods:

- The Bayesian method described above using the standard for both sexes together, which leads to the parameters of the Dirichlet prior given for the 10-year and 5-year classes in Supporting Information Table S1.
- A parametric method under the hypothesis of a Gompertz or Weibull survival distribution. The two parameters of these models are estimated by maximum likelihood for a multinomial distribution of the stages under the hypothesis of the corresponding model, assuming fixed reference data. The methods are denoted as MLG1 and MLW1.

It will be recalled that the Gompertz model, established in 1825 to describe adult mortality increasing exponentially with age, has an instantaneous mortality quotient expressed as the Weibull model was proposed by Weibull in 1951 and has been used by various authors in paleodemography to account for adult mortality with a parameter $\lambda > 1$. Its instantaneous mortality quotient is expressed as $h(t) = \lambda\rho(\rho t)^{\lambda-1}$

- The same parametric method as above, assuming that the reference data are random with a multinomial distribution for each column in the reference matrix. These methods are denoted as MLG2 and MLW2.

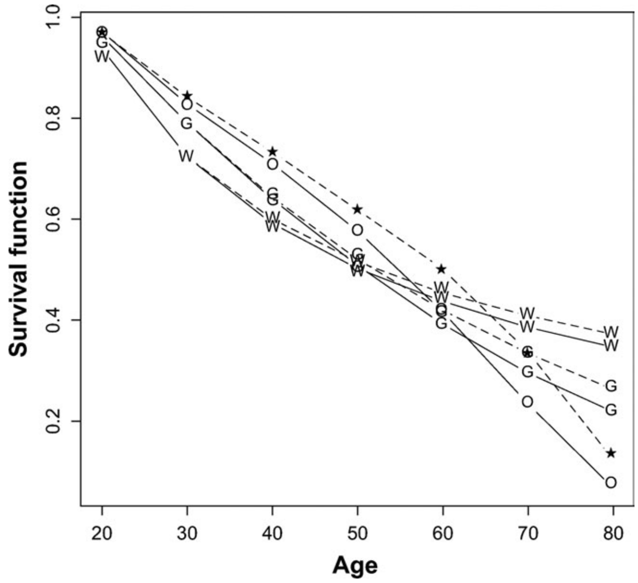

Fig. 1. Antibes, 10-year classes: survival as given by the civil records (asterisks) and as estimated by various methods—Gompertz model (G) and Weibull model (W), taking account of the random nature of the reference data or not (dashed or solid lines), and Bayesian method (circles).

First analysis: 10-year classes. The probability estimates for each of the eight age classes are given in Table 2.

The comparison between the estimates and recorded values may be summarized in various ways: Table 3 gives the sum of squared deviations and maximum deviation, and Figure 1 compares the survival distributions.

It can be seen that the Gompertz model appears to fit better than the Weibull one, and, most importantly, the two parametric methods provide estimates that fit the records much less than those obtained by the Bayesian method. With these parametric methods, whether one takes account of the random nature of the reference data or not makes little difference (the estimates may be better or worse: compare the results in Table 3 with those in Table 5 below).

It is also possible to adjust a Gompertz distribution (or any other, although the Gompertz model seems best here) to the estimates obtained by the Bayesian method, for which the most obvious way is by generalized least squares using posterior means, variances and covariances. The estimated parameters of the adjusted Gompertz distribution are then $\lambda = 0.096$ and $\rho = 0.042$ clearly different from the values estimated by maximum likelihood ($\lambda = 1.683$ and $\rho = 0.009$ for fixed references) which give a survival curve much farther from the curve observed in the records.

TABLE 4. Antibes, 5-year classes, probabilities estimated by various methods

Age classes	18–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80 +
Bayes	0.028	0.068	0.069	0.061	0.056	0.060	0.072	0.075	0.080	0.093	0.095	0.090	0.078	0.073
MLG1	0.038	0.091	0.084	0.078	0.073	0.067	0.062	0.057	0.052	0.047	0.043	0.039	0.035	0.235
MLW1	0.063	0.124	0.091	0.071	0.057	0.047	0.039	0.033	0.029	0.025	0.022	0.020	0.018	0.361
MLG2	0.038	0.092	0.087	0.081	0.076	0.070	0.065	0.060	0.055	0.049	0.045	0.040	0.036	0.256
MLW2	0.068	0.132	0.096	0.074	0.059	0.048	0.040	0.035	0.030	0.026	0.023	0.020	0.018	0.332

TABLE 5. Antibes, five-year classes: comparison between various estimates and recorded values

	Bayes	MLG1	MLW1	MLG2	MLW2
Sum of squared deviations	0.006	0.028	0.087	0.022	0.076
Maximum deviation	0.050	0.112	0.238	0.082	0.209

We can make further use of the resources of the Bayesian method by comparing, for example, the prior densities of the eight probabilities of the age classes with the posterior ones; in this example there is little difference between priors and posteriors, meaning that the estimated mortality in Antibes is likely to be close to the preindustrial standard. It is important to add that this is not an artifact related to the choice of the prior distribution[2], as will become clear from the second test example. Rather it is a strong indication in favor of the "central" nature of the Antibes mortality.

Second analysis: 5-year classes. Estimated probabilities for each of the 14 age classes are given in Table 4.

Table 5 compares these estimates with the record values and Figure 2 compares the survival probabilities they imply.

The general conclusions are similar to those for the eight-class analysis. Basically, Table 5 and Figure 2 display the same phenomena as Table 3 and Figure 1, perhaps slightly more clearly in favor of our method. Furthermore, the maximum likelihood estimation (MLE) parameters are relatively unstable; for example, the MLE parameters of the Gompertz distribution are now $\lambda = 0.872$ and $\rho = 0.015$ (to be compared with 1.683 and 0.009 for eight classes).

On the other hand, the parameters deduced from Bayesian estimation are $\lambda = 0.089$ and $\rho = 0.042$ (fairly close to those obtained with eight classes: 0.104 and 0.041). In fact we shall see below that the Bayesian method applied with different numbers of classes provides consistent results.

Ten-year estimation from 5-year estimation. Ten-year estimates may be obtained from 5-year estimates by pooling classes. Since Bayesian estimates are posterior distribution means, they need only be added; it is also possible to compare the posterior standard deviations with the classical formula for the variance of a sum (including covariance which can also be calculated as we have seen). We obtain then as probability estimates for the eight age groups and posterior standard deviations (Table 6).

These values are to be compared with the estimates and standard deviations obtained by direct analysis of the eight classes (Table 7).

The closeness with the probabilities taken from the civil records between the new and old estimates may also be compared. The results are shown in Table 8.

We see that by using the 5-year estimates

- The estimates are stable, given the order of magnitude of the standard deviations;
- The posterior standard deviations are systematically lower;
- Closeness to civil record data is improved.

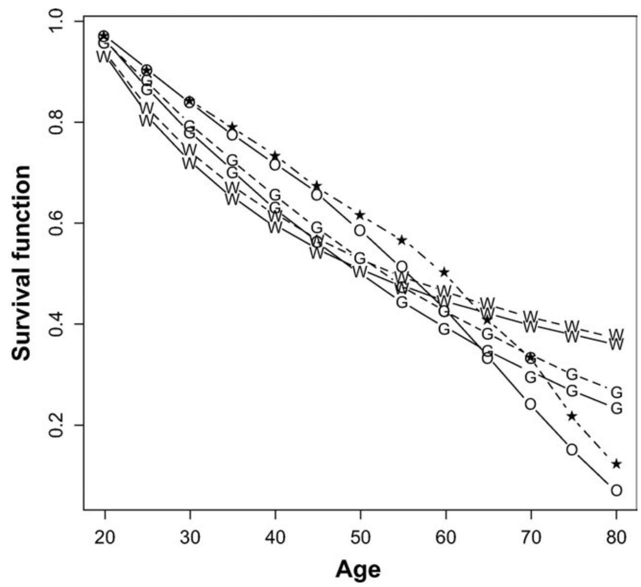

Fig. 2. Antibes, 5-year classes: survival as given by the civil records (asterisks) and as estimated by various methods—Gompertz model (G) and Weibull model (W), taking account of the random nature of the reference data or not (dashed or solid lines), and Bayesian method (circles).

Without drawing any general conclusions, it does at least seem clear that a fine division is not prejudicial to the method proposed, despite the larger number of parameters estimated.

Using specific prior information

To illustrate the use of specific prior information, we considered the data from the Royal Abbey of Maubuisson, not far from Paris (Val d'Oise, 17th–18th centuries), where historical sources allow us to reconstitute the age structure of this community of nuns and to establish their own mortality law. From 1677 to 1791, 162 nuns were buried at Maubuisson. Their names, date of death, age, and choice of burial place are recorded in the "*Register of professed nuns of Our Lady Royal known as Maubuisson, deceased since the 6th of November 1652*." With this accurate information it has been possible to construct the Maubuisson nuns' mortality table for the last years of the 18th century. The following study covers 37 exhumed adult skeletons[3], a sample (considered to be random) of the 162 nuns' bodies buried in the abbey, although it is not possible to identify the 37 individuals since their tombs are now anonymous (Séguy and Buchet, 2011).

In this example, we have considerable prior information: these were women of over 20 years of age, from noble families, with privileged living conditions that most likely reduced the mortality of the youngest ones, even without the fact that they were not subject to the high childbirth mortality of the period.

We examine the same 5-year classes as in the previous example, without the 18 to 19 class. The 10-year class analysis provides no more than it did for Antibes and is not presented here. The bone stages used are the same five as before. Their observed frequencies are (3, 5, 9, 6, 14). An analysis using a different division into bone

TABLE 6. Antibes, estimated probabilities for eight age classes and standard deviations obtained by pooling 5-year classes

Age classes	18–19	20–29	30–39	40–49	50–59	60–69	70–79	80 +
Means (estimates)	0.028	0.136	0.118	0.133	0.156	0.188	0.169	0.073
Standard deviations	0.044	0.081	0.083	0.087	0.091	0.090	0.085	0.059

TABLE 7. Antibes, estimated probabilities, and standard deviations obtained by direct analysis of the eight classes

Age groups	18–19	20–29	30–39	40–49	50–59	60–69	70–79	80+
Means (estimates)	0.028	0.144	0.119	0.134	0.155	0.187	0.164	0.069
Standard deviations	0.054	0.101	0.106	0.111	0.116	0.111	0.105	0.071

TABLE 8. Antibes, comparison with civil register values of estimates obtained by the Bayesian method for eight age classes: Direct calculation and via 14 classes

	Direct estimation	Estimation via 14 classes
Sum of squared deviations	0.008	0.007
Maximum deviation	0.055	0.051

stages (seven classes) may be found in Caussinus and Courgeau (2010): the results are very similar.

The record data show the following probabilities for the chosen age classes (Table 9).

We compare them first with the estimates obtained by the Bayesian method with three Dirichlet prior distributions whose parameters successively i) express a uniform prior one may call neutral, ii) are deduced from the preindustrial standard (female), iii) are modified from the latter to allow for the supposed lower mortality of the youngest nuns (prior reduction of 56% for the 20–29 group, 22% for the 30–39 group) (Supporting Information Table S2).

The point estimates of the p_j's (means of posterior distribution age classes) are given in Table 10 for the three priors examined, and also the probabilities corresponding to the preindustrial standard and those given by the records. Figure 3 compares these results on survival functions.

The following lessons may be drawn from the Table 10 results and the curves in Figure 3.

The recorded values are closer when the prior distribution includes our previous knowledge of the site examined.

Whatever prior distribution is chosen, the estimates drift away from the preindustrial standard towards the recorded values (even when the prior is deduced from the pre-industrial standard), revealing above-average longevity; the estimated phenomenon is, however, less marked than the "real" phenomenon" (largely because of the small sample size).

We now examine the maximum likelihood estimates obtained with a Gompertz mortality model (the Weibull model is not considered here because it is even less well suited). Figure 4 reveals a considerable distortion between the estimated survival function and the records. In fact, it would appear that the excellent fit at low probabilities for the 20 to 40 group sends the method completely off course later. The method we propose is better overall, even if it does slightly overestimate the probability of death among the youngest individuals.

If the Gompertz model is fitted by generalized least squares to the estimates obtained by the Bayesian method, as we saw above, we obtain $\lambda = 0.005$ and $\rho = 0.073$, whereas the values estimated by maximum likelihood are $\lambda = 0.002$ and $\rho = 0.067$. Figure 4 shows the effects of this clear difference in λ values. It also shows that a Gompertz model is perfectly admissible for this site, but its parameters are not those estimated by maximum likelihood[4].

Applying the method to a Gallo-Roman settlement

The Frénouville cemetery[5] (Calvados, site name "Le Drouly") lies in open fields less than 10 km from Caen in Normandy. It covers roughly 1 hectare. An exhaustive dig turned up 650 graves from two broad historical periods dated from archaeological knowledge (grave typology, burial furniture): the Gallo-Roman, from late 3rd to mid 5th century CE, and the immediately following Merovingian (Frankish), continuing until the late 7th century. The cemetery was then abandoned and burials were performed near a place of worship, perhaps Saint Martin's church, 1.5 km north in the present village. The housing that may have surrounded the cemetery has not yet been located.

The 163 Gallo-Roman remains consist of 26 juveniles and 137 adults, of whom 69 with estimated ages and 58 whose sex has been determined (see Table 11) and the 638 Merovingian remains consist of 21 juveniles and 617 adults, of whom 200 with estimated ages and 135 of determined sex (see Table 12): some graves contained more than one skeleton.

The cemetery had clear boundaries and has been fully excavated, and one of the authors has examined all the remains. This anthropological sample consequently contains all the information available for paleodemographic study.

Below we examine first the mortality structure for both sexes together for the Gallo-Roman and Merovingian periods separately, allowing us to illustrate some innovations in the estimation method we recommend; then we show how this method reveals and quantifies a difference in mortality structure between the two burial periods. Finally we examine differential male–female mortality.

Results by chronological phases

Gallo-Roman period. First the age structure at death at the Frénouville necropolis during the Gallo-Roman period was estimated using the Bayesian method, with a Dirichlet prior deduced from the preindustrial standard, in line with our earlier studies and the recommendations that follow from them. The same 14 age classes were used as for Antibes and the same five bone stage classes, for which the frequencies are 20, 10, 14, 13, and 12. Table 13 gives the means and standard deviations for the posterior and prior distributions.

TABLE 9. Maubuisson, probabilities for each of the 13 age classes taken from the abbey's register

20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65-69	70–74	75–79	80 +
0.000	0.012	0.010	0.015	0.048	0.039	0.070	0.100	0.138	0.151	0.088	0.122	0.207

TABLE 10. Maubuisson, Preindustrial standard probabilities (row 2), estimates by the Bayesian method with three priors (row 3: uniform; row 4: deduced from the standard; row 5: with modified standard), probabilities given by the abbey's register (row 6)

Age groups	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–80	80 +
Standard	0.049	0.052	0.055	0.058	0.059	0.061	0.071	0.082	0.098	0.110	0.113	0.093	0.098
Bayes-uni.	0.037	0.036	0.048	0.052	0.049	0.048	0.061	0.079	0.092	0.126	0.106	0.103	0.161
Bayes-st.	0.025	0.026	0.036	0.039	0.038	0.039	0.055	0.079	0.105	0.152	0.134	0.109	0.163
Bay-stmod	0.011	0.012	0.028	0.030	0.043	0.042	0.061	0.085	0.111	0.157	0.140	0.114	0.165
Records	0.000	0.012	0.010	0.015	0.048	0.039	0.070	0.100	0.138	0.151	0.088	0.122	0.207

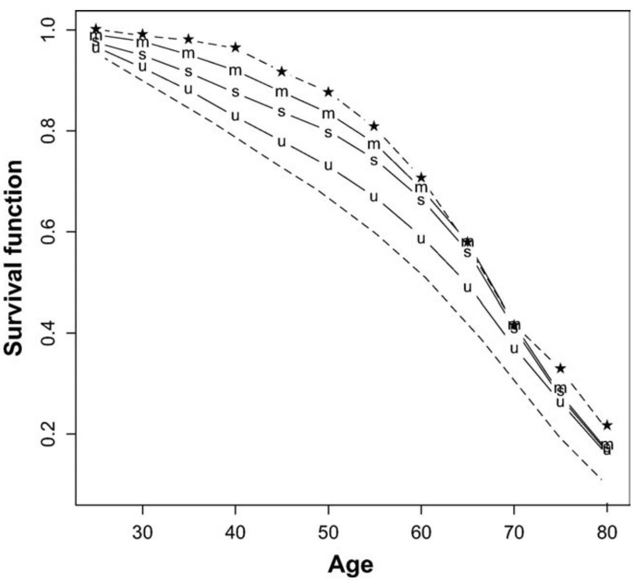

Fig. 3. Maubuisson, survival functions according to preindustrial standard (dashed curve), register data (asterisks) and three estimates with three different prior distributions: uniform (u), Dirichlet with parameters deduced from the preindustrial standard (s), Dirichlet with parameters corresponding to a "modified" preindustrial standard (m).

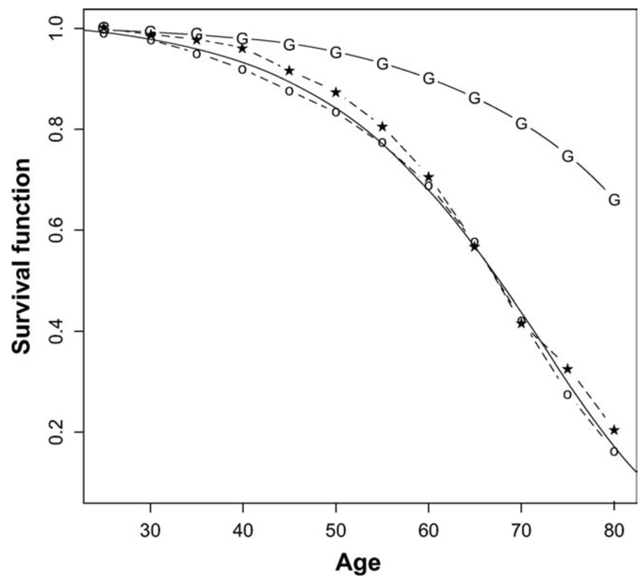

Fig. 4. Maubuisson, survival functions according to the register data (asterisks) and estimated by the Bayesian method (circles) and by maximum likelihood with Gompertz model (G). The continuous curve shows the estimated Gompertz model deduced from the Bayesian estimation.

The estimated probabilities (posterior means) are close to the probabilities of the preindustrial standard (prior means) if the large values of the standard deviations are considered; actually, the posterior standard deviations are large, in some cases even larger than those of the prior distribution. In fact the posterior distributions are very close to the prior distributions (a few examples are given in Supporting Information Figure S1; they are of particular interest when compared with the results of the following examination of the Merovingian period). The largest differences, albeit slight, might suggest mortality just above the standard for the youngest classes and consequently the opposite for the oldest. As for the high values of the posterior standard deviations, it would appear that the relatively small sample size (69) is crucial. The question is, however, whether or not this sample size is also responsible for the small variation between prior and posterior means, in other words, whether or not the age structure, estimated to be close to the standard, is an artifact due to the choice of the prior distribution. So we recalculated the estimates with a uniform prior, i.e. a Dirichlet distribution with all parameters equal to unity.

TABLE 11. Frénouville, Gallo-Roman period

Male–Female		Female		Male	
Stage	Number	Stage	Number	Stage	Number
0–0.4	20	0–0.2	12	0–0.8	5
0.5–1.3	10	0.3–0.9	0	0.9–1.5	8
1.4–2.0	14	1.0–1.8	3	1.6–2.1	10
2.1–2.8	13	1.9–2.7	5	2.2–2.8	3
2.9–4.0	12	2.8–4.0	6	2.9–4.0	6
Total	69	Total	26	Total	32

Distribution by stages of synostosis.

The results are compared with the results of the first estimation via the survival distributions in Figure 5. This figure shows estimated survival on the basis of the two prior distributions considered; to these are added the preindustrial standard survival distribution and the

TABLE 12. Frénouville, Merovingian period

Male–Female		Female		Male	
Stage	Number	Stage	Number	Stage	Number
0–0.4	92	0–0.2	33	0–0.8	30
0.5–1.3	29	0.3–0.9	6	0.9–1.5	9
1.4–2.0	22	1.0–1.8	6	1.6–2.1	11
2.1–2.8	27	1.9–2.7	3	2.2–2.8	15
2.9–4.0	30	2.8–4.0	13	2.9–4.0	9
Total	200	Total	61	Total	74

Distribution by stages of synostosis.

TABLE 13. Frénouville, Gallo-Roman period

	Posterior distribution		Prior distribution (standard)	
Age class	Mean	Standard deviation	Mean	Standard deviation
18–19	0.029	0.046	0.019	0.035
20–24	0.063	0.060	0.047	0.055
25–29	0.068	0.067	0.052	0.057
30–34	0.059	0.062	0.052	0.057
35–39	0.051	0.053	0.057	0.060
40–44	0.055	0.056	0.060	0.061
45–49	0.072	0.067	0.066	0.064
50–54	0.070	0.063	0.075	0.068
55–59	0.080	0.068	0.086	0.073
60–64	0.089	0.068	0.099	0.077
65–69	0.108	0.075	0.107	0.080
70–74	0.096	0.070	0.107	0.080
75–79	0.077	0.064	0.086	0.073
80 et+	0.083	0.065	0.086	0.073

Means and standard deviations for the posterior and prior distributions.

virtual survival distribution corresponding to the uniform prior. We see that:

- The two survival estimates are not far apart.
- Using a uniform prior, the revision from the data brings the estimates (slightly) closer to the standard.
- Using the standard, the revision slightly increases the mortality of the youngest.

It can be seen that the closeness between the first estimated mortality and the standard does not appear to be an artifact, because a prior survival curve lower than the standard is revised by bringing it closer to the standard. It is not much closer, however, which may confirm that, allowing for the major uncertainties inherent in this example, the survival curve is most likely somewhere near that of the standard but probably slightly below.

Merovingian period. The example of the Merovingian period in the Frénouville necropolis shows us how to achieve a "reliable division" into age classes, namely a division that provides the most reliable estimates. The bone stages of 200 skulls were divided into five classes (as before) with observed frequencies of (92, 29, 22, 27, 30). The Bayesian method was used with the Dirichlet prior deduced from the preindustrial standard and the same division into 14 age classes as for the Gallo-Roman period.

The values for the means and standard deviations of the posterior distributions are given in Table 14 and indicate a wide dispersal of the posterior distributions

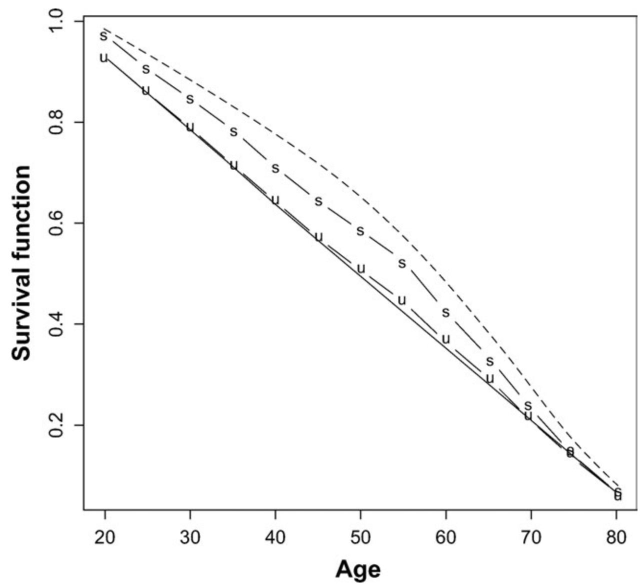

Fig. 5. Frénouville, Gallo-Roman period. Comparison of two survival functions estimated from two prior distributions: standard (s) and uniform (u); pre-industrial standard survival function (dashed line) and virtual survival function corresponding to the uniform prior (solid line).

for the first two classes, in other words, a low level of confidence to be given to the point estimates for these classes.

The results in Table 14 can be examined further by representing their posterior densities, done for four of them[6] in Figure S2 (see Supporting Information) compared with their prior densities. Confirming the initial results from Table 14, the posterior distributions are shifted to the left after the age of 35, indicating that the mortality of the older individuals is lower than the standard (and that of the younger is higher), with high accuracy for this type of problem (the relatively "marked" nature of the densities corresponds to fairly low standard deviations, described below by credible intervals). For the first two classes, the posterior distributions are shifted far to the right, indicating an excess mortality compared with the preindustrial standard. Not least it can be seen that the posterior density for the second class is clearly bimodal and that the density of the first class contains a plateau corresponding to low precision. The correlation coefficient[7] between the two distributions is high and negative (−0.778). It is also useful to consider the joint posterior density of the first two classes which is bimodal (Fig. S3, see Supporting Information) and conclude that there is a "see-saw movement" between the 18 to 19 and 20 to 29 age classes: either the 18 to 19s have a very low mortality rate, in which case the mortality of the 20 to 29s is around 0.4, or the opposite.

It is clear that the data do not allow a reliable estimate of differential mortality between the two youngest classes, but might provide a better estimate for the two together. Since the problem does not recur for any of the other age classes, we decided to attempt a division into 5-year classes from 25 to 80, between an 18 to 24 class and an over 80 class. This division into 13 age classes gives the densities shown in Supporting Information Figure S4 for four significant cases and the numerical

TABLE 14. Frénouville, Merovingian period

Age class	18–19	20–24	24–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80+
Mean	0.132	0.231	0.068	0.046	0.037	0.034	0.047	0.042	0.051	0.059	0.080	0.061	0.046	0.065
Standard deviation	0.138	0.154	0.084	0.052	0.042	0.036	0.044	0.039	0.046	0.041	0.056	0.041	0.037	0.047

Posterior means and standard deviations.

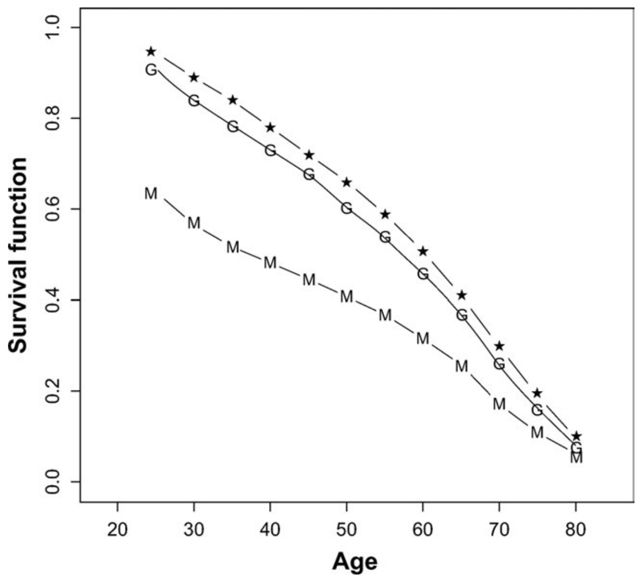

Fig. 6. Frénouville, survival functions for the Gallo-Roman (G) and Merovingian (M) periods and the preindustrial standard (asterisks).

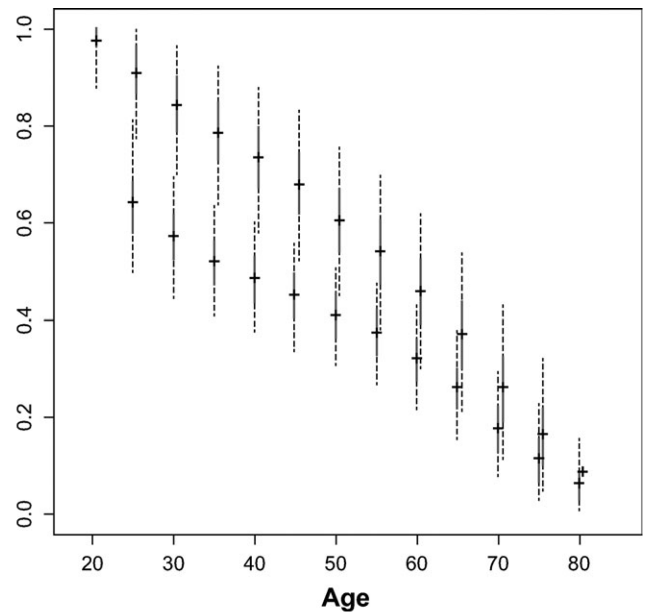

Fig. 7. Frénouville, survival functions in two periods with 50% (solid line) and 90% (dashed line) credible intervals; the Merovingian period is shifted to the left (the lack of age 20 for the Merovingian is due to the pooling of the 18–19 and 20–24 age classes).

results in Supporting Information Table S3 (posterior means, standard deviations and quartiles). It can be seen that the various estimates obtained are now reasonably reliable and precise with, in particular, very high mortality among the youngest (18–24), estimated mortality slightly above the preindustrial standard for the 25 to 30 group and lower for all the other age classes. As we shall see below, these conclusions are even clearer with the survival distribution that adds up these convergent results.

Comparisons between the two periods. The settlement data for the two periods are (20, 10, 14, 13, 12) and (92, 29, 22, 27, 30). In a χ^2 test comparison, we obtain $\chi^2 = 8.047$ for 4 degrees of freedom, giving a P value of 0.090. The two sets of data are consequently not significantly different at the most usual levels but become so at the 10% level, which is slight evidence for a difference. We examine the matter further by comparing the probability of death distributions estimated above.

Figure 6 recapitulates the two estimated survival curves and the preindustrial standard.

Figure 7 specifies the uncertainty of these estimates via 50% and 90% credible intervals; the intervals corresponding to the Gallo-Roman (resp. Merovingian) period are slightly shifted to the right (resp. left). The 50% credible intervals are clearly separated from 25 to 60 years of age and the 90% intervals overlap barely or not at all from 25 to 50. It is therefore highly likely that the two types of mortality are radically different, with, as has been said, a very high mortality of young individuals in the Merovingian period and a survival distribution close to the standard, or perhaps somewhat lower, in the Gallo-Roman period.

However, even if the results for the Early Medieval period are quite different from the preindustrial mortality standard, they are consistent with the variability we have observed in preindustrial populations.

The differences noted in distribution of death by age from one period to the other may be explained either by a variation in the age mortality distribution or by differences in population structure (by sex and age) to which the same distribution applied. Both hypotheses are plausible in the light of the archaeological evidence we possess.

Mortality results by sex

Since the study of mortality by sex may face the problem of insufficient sample size, we begin with the Merovingian period, for which the samples are larger. Mortality was estimated by the same principles for the same 13 age classes as above. Figure 8 compares the survival functions corresponding to the preindustrial standard and estimated for males only, females only and both sexes together. This provides an opportunity to note an important point about the Bayesian method. It may seem paradoxical that the estimated survival function

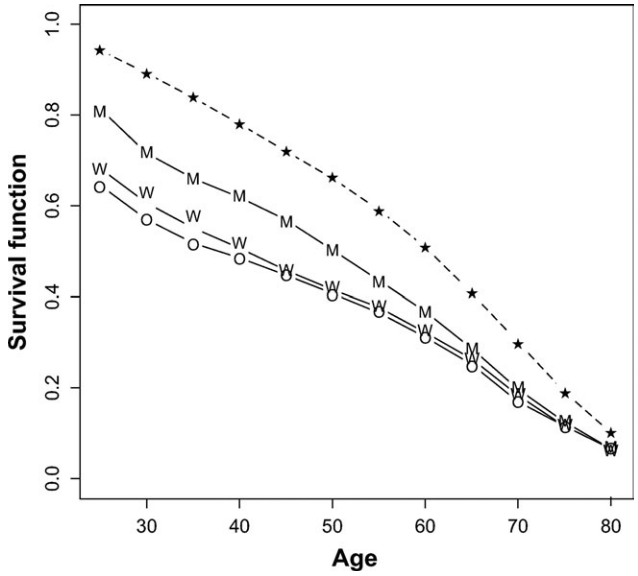

Fig. 8. Frénouville, Merovingian period. Estimated survival functions for males (M), females (W) and both sexes (circles), plus pre-industrial standard for reference (asterisks).

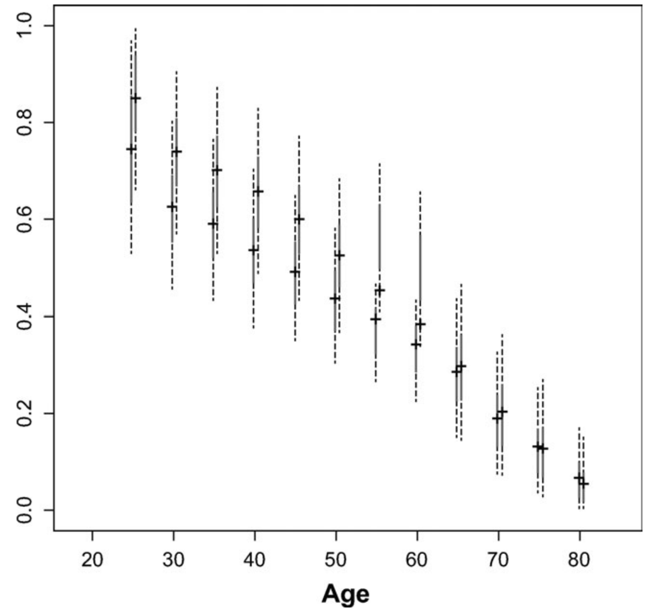

Fig. 9. Frénouville, Merovingian period. Fifty percent (solid line) and 90% (dashed line) credible intervals for male and female survival functions (female ones are shifted to the right).

for both sexes together does not lie between those of males and females. But it should be remembered that the prior distribution corresponds to the preindustrial standard, while the posterior distribution tells us how far the prior has to be revised according to the observed data. For identical relative distributions of bone stages this revision will be larger as the sample size is larger. Actually the analyses for the separate sexes are less "significant" because they are based on smaller samples (61 and 74 skeletons compared with 200)[8]. Nevertheless they confirm the overall result concerning excess mortality compared with the standard. The question remains whether it is right to assert that female mortality was higher than male mortality. To that end, Figure 9 shows the credible intervals of the estimates. It can be seen that the margin of uncertainty is wide, with credible intervals overlapping considerably, so that any real difference to men's advantage remains hypothetical.

The results for the Gallo-Roman period are similar but less marked, no doubt because of the even smaller samples. We have therefore not presented them.

Archaeological discussion

The archaeological differences noted between the Gallo-Roman and Merovingian graves, such as the sudden shift from a north-south to an east-west axis, have been interpreted in terms of cultural and/or populational change. From historical and archaeological evidence (traces of ancient land surveying, grave goods), it is noted that Roman army veterans were settled here when the cemetery was opened. Comprehensive examination of the site shows that these men who were granted a plot of land did not all come here alone, but brought wives and children. In the early 3rd century, Septimus Severus made the recruitment of barbarians to the Roman army official and, at the same time, allowed soldiers' wives to follow their husbands. The anthropological study revealed a wide diversity of buried groups from when the cemetery was opened and throughout its centuries of use, evidence of the arrival of groups from outside the region, especially from the 5th century. These population groups settled beside the local people with no apparent conflict. Paleopathological examination of the skeletons does not reveal any traumatic sequelae but rather degenerative diseases associated with everyday life. We may suppose therefore that the settlement of the first colonists occurred with no marks of violence and that the entire rural community lived relatively calm lives, even if cultural traditions in dress or burial close to relatives may have separated the groups for some generations. These living conditions, relatively similar to the expected way of life for preindustrial populations, are echoed in the estimated survival curves close to the preindustrial standard, shown to be reliable by the statistical study.

Comparison of the survival curves for the two major chronological phases reveals a definite deterioration in the chances for survival of young adults in the Merovingian period (Fig. S2, see Supporting Information). This may be explained by the archaeological conclusions. The establishment of Merovingian society after the fall of the Roman Empire was marked by major social changes accompanying the shift from Roman power and authority to "barbarian" authority. The presence of a large number of weapons, symbols more of power than warfare, reveals the emergence of a new elite favored by the new administrative structures. This shift does not seem to have occurred brutally; the paleopathological evidence reveals more accidents of daily life than wounds sustained in battle. But the shift did have consequences. Political conflict destabilized the economy and certainly caused periods of instability affecting diet (food shortages) and demography (migration, excess mortality, lower fertility).

The fact that young adults' chances of survival were worse than during the previous period may therefore be explained by the political and socioeconomic context, which, even though it did not involve violent conflict leaving marks on bones, considerably reduced the population's state of health and diet. However, what may seem to be high mortality among the Merovingian young may also be due to a difference in population structure between the two periods, with a larger number of young adults during the second phase (mortality by age would then be more or less constant but apply to more people). The attraction exercised by new elites settling on fertile land is also confirmed by the archaeological grave goods, which reveal the arrival in the Caen plain from the 5th century on of populations of eastern origin.

The credible intervals of the estimates (Fig. 7) confirm that there were indeed two types of demographic patterns (age structure and mortality).

The anthropological data show a sex ratio in favor of men (1.23 for the Gallo-Roman period; 1.21 for the Merovingian one). The statistical analysis of differential mortality by sex in both Gallo-Roman and Merovingian periods is also consistent with the anthropologists' assumption that women had worse living conditions than men, since their survival functions are below those of men. However, given the margin of uncertainty indicated by the wide overlap of credible intervals, these analyses do not provide strong confirmation of this assumption.

CONCLUSIONS

After recalling the hypothesis underlying the estimation of age by biological indicators and the difficulties encountered by the various statistical methods proposed, we demonstrate the value of a new statistical method recently introduced by the authors Caussinus and Courgeau (2010, 2011). In these two articles they establish the superiority of their approach over the various nonparametric methods commonly used. That study is supplemented here by a comparison with the maximum likelihood techniques based on a parametric model, widely used in earlier research (Hoppa and Vaupel, 2002).

By calculating the estimates obtained from two sites where mortality by age is available from records, it can be seen that our new method is again significantly better. One remarkable point is that this superiority is not due to the poor fit of the model: when a model (Gompertz in this case) is perfectly consistent with the biological data, its parameters are estimated much better by our method than by directly using the maximum likelihood method. Naturally these results need to be confirmed by further research but, together with previously published results, they do already provide a strong indication in favor of the proposed method.

Furthermore, while our method is effective for point estimates of the probability of death by age, it also has the advantage of properly allowing for the random nature of all the data available, particularly the reference data. The associated credible intervals are therefore reliable, which is far from being true for the confidence intervals associated with the methods proposed before. These credible intervals, which give a clear idea of the precision of the estimates made, are essential for comparing age at death distributions obtained for different sites and/or periods. We have also demonstrated that the division into age classes can be relatively fine without reducing the effectiveness of the method, and that conversely the fineness of the division can be controlled to make the poolings required by the data available.

These various uses of the recommended method are illustrated by the paleodemographical study of the Frénouville cemetery. We may conclude, with quantifiable precision, despite the small sample sizes, that the distribution of death by age in the Gallo-Roman period is very close to that defined by the preindustrial standard, but that this is no longer true for the Merovingian period, when deaths at a young age are significantly higher than in the preindustrial standard. On the other hand, the male–female comparison raises the hypothesis of higher female mortality, but the wide overlap of the credible intervals suggests great caution in drawing any conclusion: either the real differences are too slight, or the sample sizes are too small to reveal them.

These results corroborate and validate the hypotheses formulated by archaeo-anthropologists. In Late Antiquity, mortality differed little from the standard established for preindustrial populations, but this was no longer true two centuries later, when a new authority established itself, radically altering social structures. Paleopathological evidence and burial practices do not reveal any violent conflict likely to leave marks on bones, changes in cemetery organization or traces of destruction between the two periods. However, peaceful coexistence did not necessarily mean a healthy life: the social upheavals were bound to affect demographic behavior. We may suppose that after the settlement of the early colonists and their rapid and discreet assimilation, the population in Frénouville grew fairly fast as a result of satisfactory living conditions throughout the Gallo-Roman period and probably by the addition of young people attracted by the new Merovingian elite. In the latter period this population growth was probably accompanied by a certain deterioration in living conditions; both these factors explain lower survival chances for young adults in the Merovingian period.

Finally, it is important to emphasize that although the Bayesian character of the proposed statistical method has many advantages, as we have attempted to show, it does require the user to abandon certain reflexes due to other habits. For example, as we have pointed out, one must always bear in mind the "pivot" nature of the prior distribution. In our view, with a few exceptions, this distribution privileges the "standard" mortality among preindustrial populations, and this method explains first of all how significant is a shift from that standard, a feature of the method we regard as wholly welcome.

So, our method provides three main advantages. First, we carefully establish our reference collection and define a strict protocol to measure age indicator stages. The choice of the biological indicator is directly linked to the characteristics of European reference collections, in terms of size and associated documentation. Second, our statistical technique is based on *estimating the probability of observed skeletal stages given known age* (and not the probability of ages given biological stages), what frees us from the actual reference population's age-at-death structure. Third, we adopt a fully Bayesian approach allowing for the random nature of *all the data available*: those of the reference population and those of the archaeological observed population. We propose to center the prior distribution on what we call the preindustrial standard to take into account that we estimate a mortality law. However, on the one hand, this standard can be replaced by another mean (an example is given with the Maubuisson's nuns, but other various situations could be considered); on the other hand, it must be emphasized that a suitable prior mean is helpful but not absolutely necessary due to the large variability of the Dirichlet distribution which allows the method to provide fairly good estimates for mortality distributions far from the prior mean, as this is observed in the Frénouville example, Merovingian period.

Subject to the hypothesis of biological uniformity, paleodemographic studies could adopt our method even if their archaeological populations are far from our reference population, in time and in space. Of course, our Bayesian method can be used with any biological age indicator, provided the documentary reference samples are carefully validated.

ACKNOWLEDGEMENTS

The authors are grateful to Mrs. Maria de Graça Ramalhinho, Director of the Museu Nacional de História Natural (MHHN), and Mr. Hugo Cardoso, anthropologist at Museu Bocage in Lisbon, for making their anthropological collections available to us.

We would like to thank Roger Depledge and Catriona Dutreuilh (Ined) for the English version of this text, Antoine Pasqualini (Cepam) for enhancing the quality of the figures, and the reviewers for their comments and suggestions.

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