12-1997

Maximum Likelihood and Bayesian Estimation of Skeletal Age-at-Death from the Human Pubic Symphysis

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University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by B. S. L. Hurst entitled "Maximum Likelihood and Bayesian Estimation of Skeletal Age-at-Death from the Human Pubic Symphysis." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Anthropology.

Lyle W. Konigsberg, Major Professor

We have read this dissertation and recommend its acceptance:

Richard Jantz, William M. Bass, Karla J. Matteson

Accepted for the Council:
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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Lyle W. Konigsberg, Committee Chair

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William M. Bass

Accepted for the Council:

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Associate Vice Chancellor and
Dean of the Graduate School

MAXIMUM LIKELIHOOD AND BAYESIAN ESTIMATION OF SKELETAL AGE-AT-DEATH FROM THE HUMAN PUBIC SYMPHYSIS

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

B. S. L. Hurst

December, 1997

DEDICATION

This dissertation is dedicated with love to:

my Mom,

Susan C. Hurst

for her unfailing wisdom, unwavering strength and
her resolute faith in my ability to succeed,

and also to

my constant companions,

Pax and Joss

for the inexpressible source of joy they provide,
and for their unconditional devotion.

ACKNOWLEDGMENTS

Foremost, I would like to sincerely thank the members of my dissertation committee -- Drs. Lyle W. Konigsberg, Richard L. Jantz, William M. Bass, and Karla J. Matteson -- for their essential contributions to the successful completion of my doctorate degree and dissertation, and for the privilege of having them serve as my advisors.

I am particularly grateful to Dr. Konigsberg, my committee chairman, who inspired much of the work in this dissertation. I greatly appreciate his patience and support during the course of many discussions and revisions. I am also thankful to Dr. Konigsberg for writing the software programs necessary for this dissertation analysis. I wish to also express my sincere gratitude to my other committee members in Anthropology, Dr. Jantz and Dr. Bass. The direction of my research interests in biological anthropology are in no small part due to the guidance and influence that they have provided as mentors. I am also indebted to Dr. Matteson who gave unselfishly of her time, her knowledge and her facilities at the University Of Tennessee Medical Center in providing an ancillary research experience in anthropological genetics, as well as continuing to serve and support my research interests in the present study of this dissertation project. She has provided tremendous emotional support and academic guidance and has been a proven friend.

I would especially like to thank Drs. Judy Suchey and Darryl Katz, California State College, Fullerton, and the Los Angeles County Department of the Coroner for allowing me to use the male pubic symphysis data that was procured by Dr. Suchey in 1977. I sincerely appreciate their consideration in permitting me the opportunity to work with the data sample. I also wish to thank Dr. David Hunt, Collection Manager of the Physical Anthropology Division, Smithsonian Institution, for providing both historical and mortality data for the Terry Collection skeletal sample.

Finally, I would also like to acknowledge a family of friends, colleagues, and professors who have provided stimulating intellectual discussions and much needed humor and encouragement throughout my doctorate degree. In particular, I wish to express my appreciation to Dr. Charles Faulkner, Samantha Hens, Janet Herbruck, Dr. David Lippman, Dr. Richard Nisbett, Milton Reich, Julie Walker, and Dr. Miyo Yokota. A very special thank you to Mark Ramsey, Dr. Lisa Lefler, and Dr. Rick Fortuna.

ABSTRACT

A number of methodological problems have recently plagued studies of adult skeletal age-at-death estimation. Over the last two decades, researchers have extended considerable effort to place age estimation studies on a firmer statistical ground. However, many of the current methods can still be criticized because they make unjustifiable assumptions or use inappropriate statistical models. Much of the controversy surrounding age-at-death estimation has focused specifically on the question of applying age standards from a reference collection of known-age individuals to a target group of unknown age.

The current study, involving a large sample (n=739) of adult male pubic symphysis data, demonstrates a probability-based method in order to obtain the full posterior distribution for age-at-death conditional on observed symphyseal phases using both a maximum likelihood and Bayesian estimator. With the application of the maximum likelihood or Bayesian estimator (where the prior distribution for age is external to the reference sample) it is possible to produce age estimates that are independent of the reference sample age-at-death distribution.

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CHAPTER 1

INTRODUCTION

The determination of age-at-death is a prerequisite to all forensic and paleodemographic research on human skeletal remains. Methods of age determination are based upon maturational changes that occur in a number of areas of the skeleton from infancy through senescence. It is generally assumed that morphological changes in the skeleton correlate with chronological stages of life in the individual and, as such, can be used to estimate age-at-death.

One of the most widely recognized indicators of age-related changes in the adult skeleton is the pubic symphysis (Bass, 1987; Krogman, 1962; Stewart, 1979; Ubelaker, 1984). Even when used in conjunction with other age-related criteria, pubic symphyseal aging is generally considered more reliable than other adult skeletal indicators because of the distinctive age-related changes that are a part of normal metamorphosis. Frequently, it has been the only source of skeletal information used for the determination of adult age-at-death.

Pubic symphysis methods follow two general forms. The first is a "components" approach, in which the symphyseal surface is subdivided into diagnostic features that are individually evaluated and scored for morphological change. The distribution of individual component scores by age can either be summed for total symphyseal score or can be applied in a multiple regression analysis. The second form is referred to as a "typological" framework, in which all coexisting features on the symphyseal surface are evaluated together as one pattern of metamorphosis and then scored by age-related "phases."

Although morphological changes in the pubic symphysis have been documented from as early as the mid-18th century, nearly all research efforts have focused on the description and elementary quantification of age-related attributes. Considering the level of reliance placed on pubic symphyseal aging, it is surprising that little attention has been paid to fairly rigorous tests of accuracy or the improvement of more powerful statistical techniques for the estimate of age-at-death. Until recently, (Boldsen, 1997; Jackes, 1985; Skytthe and Boldsen, 1993), the most commonly used statistical method for analyzing the relationship between age-at-death and pubic symphyseal patterns has been the regression model (Hanihara and Suzuki, 1978; Katz and Suchey, 1986; Nemeskéri, Harsányi, and Acsádi, 1960; Sinha and Gupta, 1995; Snow 1983). However, a number of statistical assumptions can be problematic to this method due to the ordinal/categorical nature of pubic symphysis data.

The present study involves a re-analysis of known-age forensic data (n=739 males) that were used to develop age-at-death standards for the "Suchey-Brooks" system (based on Katz and Suchey, 1986) from the *os pubis*. The aging standards for the Suchey-Brooks' method are based on regression analyses of age-at-death on morphological "phase" for each of the male pubic symphyses. Such a procedure can lead to serious bias in the development of aging standards due to the implicit assumption that future estimates of age-at-death for an unknown-age target sample will have the same age-at-death distribution as the Suchey reference sample.

The purpose of this study has two objectives. The first objective is to present an appropriate statistical method that is intended for use with ordinal/categorical data that is dependent on age. Second, this analysis will demonstrate how to obtain the full posterior density for age-at-death, independent of the known-age reference sample, by using either a maximum likelihood or Bayesian estimator for adult skeletal ages-at-death. The maximum likelihood estimator uses a prior density for age that is locally uniform (uniformative), and therefore produces a posterior density that is proportional to the likelihood of age conditional on phase. The Bayesian estimator takes an informative prior for age-at-death that is based on the distribution of age from a hypothetical or external reference sample distribution. In order to obtain reference samples that are as representative as possible, age-at-death distributions will be collected from national injury mortality profiles and from a large sample of skeletal individuals from the Terry Collection.

The dissertation is organized in the following manner. The second chapter presents a review of the numerous studies of age-at-death estimation using the pubic symphysis. Chapter three provides a discussion of sources of error and bias in age-at-death estimation methods with particular emphasis on aging systems using the pubic symphysis. In particular, this chapter reviews problems associated with the uneven representation of age, sex, and "race" in reference sample standards, reference sample mimicry, and critical errors associated with the use of inappropriate statistical methodology. The fourth chapter describes the dissertation research methodology, which includes the demographic background of the Suchey and external reference samples, as well as an explanations of the statistical model and methods to be used in the analysis. Chapter five presents results of the data analysis. Chapter six provides a summary of the data analysis and discussion of the practical interpretation of the statistical results. Further conclusions address the implications for continued development of the model presented in this study.

CHAPTER 2

STUDIES OF AGE-AT-DEATH ESTIMATION USING THE PUBIC SYMPHYSIS

The first large, systematic study of age-related patterns in the pubic symphysis was conducted by Todd in 1920. His observations were based on an American White male skeletal series (n = 306) collected from the Western Reserve Medical School laboratories in the early 1900's. In his early technical notes, Todd described the symphyseal surface as resembling a "modified diaphyso-epiphyseal plane" and, as such, he anticipated that the pubic symphysis maintained useful evidence for age-related growth (1920, p. 297). He defined the pubic symphysis as being composed of five main features: a surface; a ventral border or "rampart"; a dorsal border or "rampart"; a superior extremity; and a inferior border. Using these features, Todd developed a ten-phase typological aging system from a series of age-progressive patterns of morphological change. He described the patterns at the approximate midpoint of every phase from 18 to 50+ years (Table 2.1).

Todd grouped the ten-phase system into three broad developmental periods. Phases I-III were known as the post-adolescent stages in which the surface is characterized by horizontal ridging and furrows. The second period

Table 2.1 *Todd's "Ten-Phase" System for the Pubic Symphysis* (1920)

Phase 1.	Age 18-19: Typical adolescent ridge and furrow formation with no sign of margins and no ventral beveling.
Phase 2.	Age 20-21: Foreshadowing of ventral beveling with slight indication of dorsal margin.
Phase 3.	Age 22-24: Progressive obliteration of ridge and furrow system with increasing definition of dorsal margin and commencement of ventral rarefaction (beveling).
Phase 4.	Age 25-26: Completion of definite dorsal margin, rapid increase of ventral rarefaction and commencing delimitation of lower extremity.
Phase 5.	Age 27-30: Commencing formation of upper extremity with increasing definition of lower extremity with increasing definition of lower extremity and possibly sporadic attempts at formation of ventral rampart.
Phase 6.	Age 30-35: Changes in symphyseal face and ventral aspect of pubis consequent upon diminishing activity, accompanied by bony outgrowths into pelvic attachments of tendons and ligaments.
Phase 7.	Age 35-39: Changes in symphyseal face and ventral aspect of pubis consequent upon diminishing activity, accompanied by bony outgrowths into pelvic attachments of tendons and ligaments.
Phase 8.	Age 39-44: Smoothness and inactivity of symphyseal face and ventral aspect of pubis. Oval outline and extremities clearly defined but no "rim" formation or lipping.
Phase 9	Age 45-50: Development of "rim" on symphyseal face with lipping of dorsal and ventral margins.
Phase 10.	Age 50 and upwards: Erosion of and erratic, possibly pathological osteophytic growth on symphyseal face with breaking down of ventral margin.

included Phases IV-VI, during which the surface begins to smooth and an oval outline surrounding the symphyseal surface becomes delineated. The third period covers Phases VII-X and describes a period of overall quiescence and eventual articular degeneration.

Additional studies by Todd examined a sample of 90 adult American Black males, aged 17 to 45 years, which he compared with his original collection of American Whites (1921, II). Todd concluded that age-phase distributions were essentially in agreement for both groups, although morphological changes in the Black sample appeared to be more accelerated during the fourth and fifth decades (Phase IX) of metamorphosis. For comparison, Todd also examined a small and restricted series of adult American Black (n=22) and American White (n=47) female skeletons aged 16-74 years. The age-phase distributions were similar between the female samples and comparable to the age-phase distributions for the male samples. One difference noted was that age-related changes in symphyseal patterns appeared more accelerated in the initial phases (I, II, II) for both female groups (1921, Part III & IV).

Limitations of the Todd system relate to critical problems regarding the accuracy of "documented" skeletal ages, as well as the irregular distribution of age frequencies generated by his study samples (Katz and Suchey, 1986 and references therein). Even Todd himself acknowledged the unusual five-year peaks of mortality occurring at ages 35, 40, 45, 50 and 60 years (1920, p. 289), which may have resulted from cadaver ages that were submitted by rounding to the nearest decade or midpoint of the decade. It was noted that in some cases the municipal records were not always found to be reliable. Likewise, in some instances a chronological age may have been assigned by an anatomist in charge of cadaver preparation, particularly when the individual was not known and no living relatives could be contacted.

Another problem adding to the concerns over sample bias includes the fact that certain skeletal variations were eventually removed from the study if they were found not to fit the existing standards constructed for morphological development (Todd, 1923). If the articular face of the pubic symphysis was found to be atypical to the standard patterns of pubic metamorphosis, individuals were reassigned as alternative types, thus inappropriately reducing the variability of the sample data.

In 1955, Brooks re-examined Todd's American White male and female samples from Western Reserve University (WRU) along with an archaeological collection of prehistoric Native American skeletons from California (n=470) curated by the University of California Museum of Anthropology (UCMA). The study was conducted to determine why archaeological samples of aboriginal California Indians had consistently been found to have a mean age of death that was less than 30 years. To investigate this problem, Brooks utilized adult age estimates derived from cranial suture closure and pubic bone morphology.

Brooks also attempted to examine the extent to which possible "racial/ethnic" and sex differences could be detected by either method.

For pubic age determination, a series of 10 pubic symphyses were selected based on matched description of the Todd "type" specimens, and adopted as the "reference" standard for the determination of age in both the modern and archaeological collections. The mean ages and standard deviations were calculated for the male and female series in both collections. While there was no apparent way to check the accuracy of either cranial or pubic age estimates for the archaeological collection (UCMA), the documented ages and the mean age estimates for the WRU collection were plotted on scattergrams as an indirect measure of the reliability of the methods. Specific conclusions regarding male symphyseal changes determined that Todd's "type" specimens tended to overage the Western Reserve male sample. As a result, the Todd phase limits were adjusted by shifting Phases V-VIII, making them approximately three years younger. With these modifications, it was possible to increase the percentage of correct predictions of age within phase limits from 30% to 61% in the WRU collection (1955, pg. 583). Her conclusions, however, stress the need for further investigation of racial/ethnic and sex differences, and the frequencies of "alternative patterns" of symphyseal metamorphosis.

In 1957, McKern and Stewart proposed a different approach to Todd's typological ten-phase system and developed a formula for summarizing morphological variability by subdividing the symphyseal surface into three components: a symphyseal rim and a ventral and dorsal demiface. Each symphyseal component was scored for five successive stages of chronological development (Tables 2.2.1 and 2.2.2). Symphyseal scores were calculated by totaling the three components. Age limits for the symphyseal scores were based on the age distribution of the study sample from earliest to latest in each stage of all three components. A mean age and standard deviation were then calculated for the range of ages associated with each of the symphyseal scores.

The McKern and Stewart sample included skeletal remains from 349 American male soldiers killed during the Korean War. Age and race were established using U.S. military records. The skeletal series was predominantly "Caucasoid" (90.4%), with only 35 of the soldiers identified as "Negroid" and one documented as "Mongoloid." A separate racial analysis was not investigated in view of the small proportion of individuals that were observed to be non-Caucasian.

The McKern and Stewart method is less rigid than Todd's typological system because it allows for the aging of individuals that fall outside of "typical" development. Therefore, individual variability poses fewer problems in the determination of age. A major disadvantage of this system is the age distribution of the skeletal series, which lacks individuals in later decades. Only 1.5 % of the total sample is past 30 years of age and no individuals were beyond

Table 2.2.1 *McKern and Stewart's Component Stages for the Pubic Symphysis* (1957)

Component I --<u>Dorsal Plateau</u> :

0. Dorsal margin absent.
1. A slight margin formation first appears in the middle third of the dorsal border.
2. The dorsal margin extends along the entire dorsal border.
3. Filling-in of grooves and resorption of ridges to form a beginning plateau in the middle third of the dorsal demi-face.
4. The plateau, still exhibiting vestiges of billowing, extends over most of the dorsal demi-face.
5. Billowing disappears completely and the surface of the entire demi-face becomes flat and slightly granulated in texture.

Component II -- <u>Ventral Rampart:</u>

0. Ventral beveling is absent.
1. Ventral beveling is present only at the superior extremity of ventral border.
2. Bevel extends inferiorly along ventral border.
3. The ventral rampart begins by means of bony extensions from either or both of the extremities.
4. The rampart is extensive but gaps are still evident along the earlier ventral border, most evident in the upper two-thirds.
5. The rampart is complete.

Component III -- <u>Symphyseal Rim:</u>

0. The symphyseal rim is absent.
1. A partial dorsal rim is present, usually at the superior end of the dorsal margin, it is round and smooth in texture and elevated above the symphyseal surface.
2. The dorsal rim is complete and the ventral rim is beginning to form. There is no particular beginning site.
3. The symphyseal rim is complete; enclosed symphyseal surface is finely grained in texture and irregular or undulating in appearance.
4. The rim begins to break down; the face becomes smooth and flat and the rim is no longer round and sharply defined; some evidence of lipping on the ventral edge.
5. Further breakdown of the rim (especially at the superior ventral edge) and rarefaction of the symphyseal face; also some disintegration and erratic ossification along the ventral rim.

Table 2.2.2 *McKern and Stewart's Male Age Limits* (1957)

Stage	Age Range	Modal Age
	Component I:	
0	17.0 - 18.0	17.0
1	18.0 - 21.0	18.0
2	18.0 - 21.0	19.0
3	18.0 - 24.0	20.0
4	19.0 - 29.0	23.0
5	23.0 +	31.0
	Component II:	
0	17.0 - 22.0	19.0
1	19.0 - 23.0	20.0
2	19.0 - 24.0	22.0
3	21.0 - 28.0	23.0
4	22.0 - 33.0	26.0
5	24.0 +	32.0
	Component III:	
0	17.0 - 24.0	19.0
1	21.0 - 28.0	23.0
2	24.0 - 32.0	27.0
3	24.0 - 39.0	28.0
4	29.0 +	35.0
5	38.0 +	

50 years. As a result, the accuracy of age estimation beyond middle age is likely to be problematic.

In 1960, Nemeskéri, Harsányi, and Acsádi examined 105 skeletons of known age and sex utilizing radiographic translucency of the proximal humerus and femur, metamorphosis of the pubic symphysis and cranial suture closure (reviewed by Acsádi and Nemeskéri, 1970). Making slight revisions to previous methods of age estimation, the authors re-defined a series of age-related phases for the humerus, femur and the pubic symphysis and applied these criteria to their sample specimens. The means were calculated for each of the respective phases for all of the skeletal indicators from the known age distribution of the sample.

Linear and quadratic regression analyses were used to determine the relationships for phase and mean age of each method, and regression coefficients were graphed for comparison. The resulting statistics suggest that while endocranial suture closure appears to begin early, advance quickly and slow down at older ages, the changes of the humerus, femur, and pubic symphysis instead begin slowly and accelerate more rapidly with advancing age. The authors propose that their "complex" methodology can more accurately approximate chronological age by averaging extreme values that may be due to advanced or retarded morphological states between the skeletal indicators.

In 1973, Gilbert and McKern studied the pubic symphyses of American females (n=103) ranging in age from 14 to 59 years (Table 2.3). Using a system analogous to the "symphyseal score" established by McKern and Stewart, the authors observed that the location and development of bony changes was indeed different in their female sample (differences quite possibly caused by the trauma of childbirth).

Previous investigations had noted marked differences between males and females for age-related metamorphic changes of the *os pubis* (Brooks, 1955; Stewart, 1957; Todd, 1921). When compared to aging standards for a male, a female of the same age could appear either ten years younger based on the appearance of the ventral rampart or ten years older based upon the appearance of the dorsal plateau (Gilbert, 1973).

Although symphyseal changes were seen to begin in both sexes at about the age of 17 years, the authors suggest the rate of maturation is much "steeper" in males between 17-25 years, while in females the rate is more "gradual and regular" for the period of 17-40 years. After 40 years, the rate of maturation in females appears to decline abruptly. The authors speculate the decline may represent the approximate onset of menopause. As a method to overcome these discrepancies, Gilbert and McKern developed six definition stages for each of the three symphyseal components and established new correlations for age estimation in females.

Table 2.3 *Gilbert and McKern's Female Age Limits (1973)*

Stage	Age Range	Modal Age
	Component I:	
0	14.0 - 24.0	18.00
1	13.0 - 25.0	20.04
2	18.0 - 40.0	29.81
3	22.0 - 40.0	31.00
4	28.0 - 59.0	40.80
5	33.0 - 59.0	48.00
	Component II:	
0	13.0 - 22.0	18.63
1	16.0 - 40.0	22.52
2	18.0 - 40.0	29.64
3	27.0 - 57.0	38.77
4	21.0 - 58.0	40.90
5	36.0 - 59.0	48.50
	Component III:	
0	13.0 - 25.0	20.23
1	18.0 - 34.0	25.75
2	22.0 - 40.0	32.00
3	22.0 - 57.0	35.60
4	21.0 - 58.0	39.90
5	36.0 - 59.0	49.40

Hanihara and Suzuki (1978) conducted a study to assess age estimation using multiple regression analysis. The study involved a small (n=70) combined-sex sample of contemporary Japanese. Borrowing from different scoring elements in the Todd and the McKern and Stewart methods, a set of seven morphological features (horizontal ridges and furrows, pubic tubercle, lower end, dorsal margin, superior ossific nodule, ventral beveling, and symphyseal rim) were selected for the assessment of age and scored on a scale of 1 through 4. Partial correlation coefficients were calculated using the scores from each of the seven morphological features. Results of the multiple regression analysis between observed and estimated ages show a correlation coefficient of 0.9237. An analysis of variance for the regression was considered significant (p=0.10). A major drawback of this investigation, however, is the narrow distribution of age within their sample (18 to 38 years) and relatively small sample size. As a result, the authors suggest that when the estimate of an unknown-age specimen is expected to be younger or older than the study sample age distribution, other methods should be utilized.

Suchey (1979) tested the Gilbert and McKern system (1973) for aging the female *os pubis*. Her study involved observations of 11 female pubic symphyses of known age that were examined by 23 physical anthropologists associated with the American Academy of Forensic Sciences. Results of the components and summary age analysis revealed a considerable amount of variation by the various investigators. Considering the rather broad age ranges of the Gilbert and McKern method, only 51% of the assessments yielded age ranges that included the known age of the specimens in question. Discouraging results led the author to conclude the method was unreliable and difficult to apply.

Snow (1983) proposed a substitution of regression equations for predicting age from the symphyseal scores produced by both the McKern and Stewart and Gilbert and McKern tabular data. Using the published data for both sexes, Snow suggests that regression should result in more accurate age estimates since the sample data are treated as a whole rather than as a series of independent subsamples. However, the regression results presented by Snow do not differ significantly from the age estimates originally determined by tabular symphyseal scores.

Meindl, Lovejoy, Mensforth, and Walker (1985) conducted a comparative test of aging standards (Todd, McKern and Stewart, Gilbert and McKern, Hanihara and Suzuki) used for pubic symphyseal aging. The study combined male and female subsamples (n=96) from the Hamann-Todd Collection. Results demonstrated that correlations between known and estimated age were most accurate using the Todd method. However, all systems performed poorly by "under-aging" in higher age categories. To adjust for this problem, the original ten-phase Todd system was collapsed into five major "biological stages"

(1985, pg. 36) and applied to a new combined sample (n=109) for further testing.

Results from the second sample (Table 2.4) using the modified Todd system, appeared to show general improvement across all age categories, although bias in "underaging" the oldest age category is still present. While the authors suggest that the use of the "biological stages" is more sensitive than the typological system, the small size and uneven age structure of the sample make these conclusions a matter of subjective interpretation. Although the authors conclude that pelvic indicators remain among the best available for adult age estimation, they suggest the use of multiple age-related traits to increase the accuracy of age-at-death estimates.

Table 2.4 *Meindl et al.'s Biological Stages of Symphyseal Metamorphosis* (1985)

	Biological stage	Todd phase	Ages
1.	Preepiphyseal	1-5	20-29
2.	Active epiphyseal	6	30-35
3.	Immediate postepiphyseal	7	36-40
4.	Maturing; predegenerative	8	40-44
5.	Degenerative	9-10	45+

Jackes (1985) recommended fitting normal distributions within symphyseal phases as a method for standardizing age categories that are frequently underrepresented. Jackes suggested that use of mean values for estimated age scores will produce age-at-death distributions that are both biased and inaccurate. In response to this problem, she proposed that ages be distributed according to a 95% probability assumed under a normal distribution (± 2 SD). In this way, Jackes suggested that she was able to smooth out the systematic distortions that occur between different aging techniques and provide a more accurate estimation of age among methods and comparative samples. However, since the distribution of age within a phase is dependent on the total age-at-death distribution, it is unlikely that the age-at-death for individuals within any or all particular stages will be "normally" distributed.

In 1986, Katz and Suchey presented results from regression analyses of 739 adult "multi-racial" males between the ages of 14 and 92. The sample was collected from autopsied cases at the Los Angeles County Coroner's office in 1977 and analyzed using the original Todd (1920) and McKern and Stewart (1957) methods during 1978 - 1979. From 1978 - 1983, an interobserver error study was conducted among twenty-five forensic anthropologists using the original Todd, and McKern and Stewart methods. Both studies are reported fully in Suchey, Wiseley, and Katz (1986). It was found that examiners could not consistently differentiate between the morphological patterns, so various age categories from each method were adjusted and modified forms of the Todd and McKern and Stewart method's were constructed. Todd's ten-phase system was reduced to six stages (combining Todd's phases 1, 2, and 3; 4 and 5; 7 and 8) with revised age limits. The McKern and Stewart method was adjusted to a "pattern analysis" rather than the original combined (component) symphyseal score.

Regression analyses were performed using "age" as the dependent variable on each of the four methods. In general, the Todd and modified Todd systems fared better than the modified and original McKern and Stewart methods, but all methods performed poorly when applied to individuals with an age greater than 40 years. Truncation strategies to eliminate older individuals resulted in substantial improvement. Overall differences between the original and modified versions of the Todd system were considered of little statistical importance. However, regarding the use and implementation of either system, the authors suggested that the modified Todd six phase system is simply "easier" to use.

From 1985 to 1988, Suchey and Brooks continued to study the male pubic bone in greater detail. The sample of 739 male pubic bones was re-examined "blind" by both investigators, focusing on the refinement of morphological descriptions for each of the six phases. The original statistics from the 1986 study were re-run and evaluated so as to incorporate any data that had been re-classified by the investigators during re-examination. A set of male casts were made following the selection of two pubic bones that were chosen to represent each of the six morphological phases; each phase was represented by both an early and later pattern of metamorphosis (Suchey and Brooks, 1988).

Following the refinement of standards for the male pubic sample, Suchey and Brooks re-initiated studies of age-related changes for adult females. Further research included a subsample of 273 female pubic bones taken from a collection of 486 females previously reported in the literature (Suchey, Wiseley, Green, and Noguchi, 1979). Fıom this data, Suchey and Brooks established a female aging system (Suchey, Brooks and Rawson, 1982) analogous to the six phase aging method for adult males.

Eventually, a universal system was developed for both sexes (Brooks and Suchey, 1990) focusing on key morphological changes that were observed in males and females, such that a single set of descriptions could be universally applied. Refined descriptions for both sexes were formulated along with descriptive statistics relating to the application of the Suchey-Brooks pubic aging method (Table 2.5). Separate cast models for males and females were, however, necessary in order to correctly evaluate the pubic bones in the applicable phases by sex.

Table 2.5 *Suchey-Brooks System for Symphyseal Aging* (1990)

Phase I.	Symphyseal face has a billowing surface (ridges and furrows) which usually extends to include the pubic tubercle. The horizontal ridges are well-marked and ventral beveling may be commencing. Although ossific nodules may occur on the upper extremity, *a key to the recognition of this phase is the lack of delimitation of either extremity (upper or lower).* [95% age range - males: 15-23, females: 15-24]
Phase II.	The symphyseal face may still show ridge development. The face *has commencing delimitation of lower and/or upper extremities occurring with or without ossific nodules.* The ventral rampart may be in beginning phases as an extension of the bony activity at either or both extremities. [95% age range - males: 19-34, females: 19-40]
Phase III.	Symphyseal face shows lower extremity and *ventral rampart in process of completion.* There can be a continuation of fusing ossific nodules forming the upper extremity and along the ventral border. Symphyseal face is smooth or can continue to show distinct ridges. Dorsal plateau is complete. Absence of lipping of symphyseal dorsal margin; no bony ligamentous outgrowths. [95% age range - males: 21-53, females: 21-46]
Phase IV.	Symphyseal face is generally fine grained although remnants of the old ridge and furrow system may still remain. *Usually the oval outline is complete at this stage, but a hiatus can occur in ventral rim.* Pubic tubercle is fully separated from the symphyseal face by definition of upper extremity. The symphyseal face may have a distinct rim. Ventrally, bony ligamentous outgrowths may occur on inferior portion of pubic bone adjacent to symphyseal face. If any lipping occurs it will be slight and located on the dorsal border. [95% age range - males: 26-70, females: 23-57]
Phase V.	*Symphyseal face is completely rimmed with some slight depression of the face itself, relative to the rim.* Moderate lipping is usually found on the dorsal border with more prominent ligamentous outgrowths on the ventral border. There is little or no rim erosion. Breakdown may occur on superior ventral border. [95% age range - males: 25-83, females: 27-66]
Phase VI.	*Symphyseal face may show ongoing depression as rim erodes.* Ventral ligamentous attachments are marked. In many individuals the pubic tubercle appears as a separate bony knob. The face may be pitted or porous, giving an appearance of disfigurement with the ongoing process of erratic ossification. Crenulations may occur. The shape of the face is often irregular at this stage. [95% age range - males: 42-87, females: 34-86]

The estimation of age-at-death from the pubic symphysis continues to be one of the most extensively used adult skeletal aging techniques. As a general rule, it is considered one of the most reliable methods available for the estimation of adult age-at-death, and as well may be the only method used in complex cases where a fully articulated skeleton is not present. Adult age estimates from the Todd, McKern and Stewart, and Suchey-Brooks methods continue to be regularly cited in forensic and skeletal biology textbooks.

CHAPTER 3

SOURCES OF INACCURACY AND BIAS IN THE DEVELOPMENT OF SKELETAL AGE-AT-DEATH STANDARDS

Traditional methods of determining skeletal age-at-death have come under recent scrutiny, with much attention focusing on problems of methodological error and bias. Much of this debate, ignited from criticisms by Bocquet-Appel (1986) and Bocquet-Appel and Masset (1982, 1985), has centered on the question of the uncertain accuracy of applying age standards from a "reference" collection of known-age individuals to an unrelated "target" sample of individuals of unknown age.

The methods for estimating skeletal age-at-death have largely been emended from forensic identification techniques developed during the 1960's and 1970's. With the subsequent application of age estimation methods to the study of paleodemography, researchers set out to refine the traditional approaches in order to develop techniques that would allow for comparisons of historic and prehistoric age-at-death distributions among sites and over time (Jackes, 1992). However, until recently, relatively little attention was paid to the objectivity of age assessment techniques and the need to improve methodologies from a statistical perspective.

During the last 15 years, a number of studies have readdressed well-known concerns over methodological reliability by questioning the conventional statistical assumptions associated with the development of skeletal age-at-death standards (Bocquet-Appel and Masset 1982, 1985, 1996; Buikstra and Konigsberg, 1985; Jackes, 1985; Konigsberg and Frankenberg, 1992, 1994; Lanphear, 1989; Piontek and Weber, 1990; Siven, 1991; Van Gerven and Armelagos 1983). To some degree, this pursuit has resulted in further debate and greater disparity over the resolution of appropriate statistical techniques used to solve these problems.

A review of ongoing controversies and concerns in the study of human skeletal age-at-death estimation involves the following issues: [1] effects of error and bias in adult aging methods developed from reference samples that are not proportionately representative in terms of the distribution of age and sex classes; [2] the potential for the reference sample age-at-death distribution to be superimposed on the age structure of the target sample or target individual; and finally [3] the use of inappropriate statistical methods for the development of age-at-death standards.

I. Reference Sample Representativeness

Bocquet-Appel and Masset (1982, 1985) have argued that adult age-at-death estimation methods are developed from skeletal reference populations where age and sex classes are poorly represented, and as such, are prone to produce biased estimates of age. In addition, they claim that aging standards developed in modern populations cannot be accurately applied in prehistoric sample contexts. Lovejoy, Meindl, Mensforth, and Barton (1985a) propose that correlations of skeletal age-at-death indicators and chronological age may actually be higher in archaeological collections where the samples are likely to be more culturally and genetically homogeneous in nature.

With respect to adult age estimation, under-representation and potential misclassification of older adults is likely to be the result of several different factors. For example, several studies have demonstrated that many commonly used adult age indicators (e.g. pubic symphysis, auricular surface, cranial sutures, and histomorphometry) do not exhibit systematic age-related changes after 50 years (Brooks, 1955; Lovejoy, Meindl, Pryzbeck, and Mensforth, 1985b; Suchey et al., 1986; Walker, Lovejoy, and Meindl, 1994). Accordingly, some adult aging techniques, such as the Todd pubic symphysis system or the Lovejoy et al. (1985b) auricular surface method, may tend to underage individuals that are 50 years or older. In contrast, the pubic symphysis method defined in the Nemeskéri et al. method (1960), results in age estimates of too many individuals between the ages of 45 - 60 years (Jackes, 1985). Brooks and Suchey (1990) also found the Acsádi-Nemeskéri method focused only on the description of age changes in the early and late morphological stages. There are also a number of pubic symphysis aging methods that do not distinguish individuals above the age of 50 years simply because the reference samples included only a few or no individual differences beyond this age (i.e. Hanihara and Suzuki, 1978; McKern and Stewart, 1957; Meindl et al., 1985).

The areas of sex-specificity and racial differences have also been included as points of possible weakness in the development of adult age-at-death standards. Substantial sex bias has been observed, particularly in pubic symphysis aging techniques (Rogers and Saunders, 1994; Suchey, 1979), and most methods are known to be more reliable for males than for females (Brooks, 1995; Katz and Suchey, 1986; Stewart, 1957).

Although Todd (1921) included females in his early analyses of pubic symphysis morphology, the sample of American Black (n=22) and American White (n=47) females was too small to investigate for sex differences. Therefore, the development of his original ten-phase symphyseal aging system was based solely on American white males. The Gilbert and McKern system, developed specifically for females (1973), was later shown to be unsatisfactory due to the notable increase in variability found with additional testing of female pubic symphyses (Suchey, 1979). Accounting for known differences of age-related metamorphoses for the male and female pubic symphysis, Brooks and Suchey (1990) developed a set of unisex descriptions that focus on fundamental morphological changes that are universal to both sex samples.

The issue of racial differences in aging has not been rigorously examined. There are virtually no large-scale studies using known-age skeletal collections that include a representative distribution of "races" with regard to socially-defined racial categories. The exception, however, is a well-documented "multi-racial" sample (n=704) of male pubic symphyses examined by Katz and Suchey (1989). Their analysis identified some differences between races, stating that Blacks and Mexican-Americans with advanced patterns of metamorphosis presented lower averages of ages than do Whites. The authors were unable, though, to detect consistently distinctive morphological characteristics that could distinguish the "racial identity" of individuals.

II. Reference Sample Mimicry

One of the most heated debates in the controversy over the reliability of skeletal age-at-death estimates is the issue of "reference sample mimicry." Bocquet-Appel and Masset (1982, 1985) have argued that estimated age structures of paleodemographic profiles reflect nothing more than the age-at-death distribution of the reference samples used to classify them. Consequently, for any given skeletal aging method, the overall direction of the anthropologist's age estimates will be biased and affected by the age-at-death distribution contained in the reference collection.

Other researchers, however, disagree and have attempted to demonstrate that Bocquet-Appel and Masset's warnings were perhaps grimly and greatly overstated. Van Gerven and Armelagos (1983) addressed the problem of reference sample bias in a study comparing both archaeological and reference sample age-at-death data. The mortality study included two prehistoric Nubian skeletal groups and the Todd American male reference series, which was used to estimate age-at-death for the Nubian samples. Cumulative mortality profiles for all three samples were compared and considered dissimilar enough from one another for the authors to reject any evidence for mimicry between the reference and target age distributions. In a similar effort, Mensforth (1990) analyzed mortality profiles for two prehistoric populations (Carlston Annis Bt-5 and Indian Knoll) and compared them with the McKern and Stewart Korean War dead sample, which was used as the reference aging standard for the archaeological samples. Mensforth found that age distributions for both prehistoric groups were significantly different from the McKern and Stewart collection. He therefore concluded that the reference distribution of age-at-death had not been imposed on the structure of ages in the archaeological samples.

Lanphear (1989) compared estimated and real age demographic distributions using a 19th century New York cemetery sample and historic records as a test for reference sample mimicry. To test the relative representativeness of both samples, lifetables were constructed using adult skeletal age-at-death estimates from the Monroe County Almshouse Cemetery and documented reports from nearby Brighton town clerk's vital registration records. The author found no statistically significant differences between the skeletal age estimates or the vital records for life expectancy, survivorship, or age-at-death distribution. Although Lanphear acknowledged that neither of the lifetable sample distributions may in fact represent the once living population, she concluded that skeletal reference standards used in the mortuary study had not affected the accuracy of the age-at-death estimates when compared to the vital registration records for the same historical time period. Piontek and Weber (1990) investigated differences between estimated and reported age distributions by comparing age-at-death estimates from a church cemetery used between 1350 and 1650 AD and documented age records from the same parish registers during the nineteenth century. Comparisons of cemetery sample estimates of age and documented age records were found to be nearly equivalent in distribution. Due to the similarities between sample distributions, Piontek and Weber concluded that the estimated ages of the cemetery sample had not been influenced by the age distribution of the reference sample and were in fact an accurate reflection of the mortality structure between the 14th-18th and 19th century.

Scheuer and Bowman (1995) compared skeletal remains from 19th-century crypts of the St. Bride's Church in London with documented death records from St. Bride's parish mortuary books. Age-at-death profiles were drawn for skeletal data from church crypt burials and vital records data from individuals buried in two adjoining church cemeteries, as well as for those individuals documented as being interred in the church crypt. Results suggested that the age-at-death profiles obtained from the skeletal data were not similar to the documentary evidence from the crypt and cemetery mortuary books. The authors concluded that the lack of correlation between skeletal and documented data was probably due in part to sample biases such as discrepancies in the historical record or cemetery data that were not representative of the general parish population.

Saunders and colleagues (1995) compared skeletal data from the historic St. Thomas' Anglican Church cemetery with church parish records for the same period in which the cemetery was used, along with secular demographic data from decennial censuses of the local Belleville community during the 19th century. The demographic profiles for adult skeletal and parish record data were found to be "statistically indistinguishable" (p. 102), despite major discrepancies of over-representation of infant burials in the skeletal sample. Age distribution values for the Belleville censuses were also found to show similar patterns of survivorship compared with the estimated skeletal remains and the parish records, although conclusions were considered preliminary.

Sirianni and Higgins (1995) expanded upon Lanphear's (1989) earlier study of a 19th-century Monroe County poorhouse cemetery located in

Rochester, New York. Additional historical data was provided from the Mt. Hope Cemetery interment documents, which included a two year period in the mid-1800's during which the cemetery was assumed to be in use by the poorhouse. The Mt. Hope cemetery documents were added to the Brighton town clerk's vital registration records and compared with the estimated skeletal ages-at-death for the Monroe County almshouse cemetery sample. Sirianni and Higgins found that the distribution of estimated age-at-death in the adult female skeletons more closely resembled the age distribution found in the female historical documents, while the estimated ages for the adult male skeletons did not conform with the vital records for adult males. The authors determined that the demographic differences between the cemetery and historical death records for adult males could be explained given the depressed socioeconomic status and potential transient nature of the almshouse male residents.

While the implications of the previous studies are logical, the pivotal data necessary to refute reference sample mimicry is wanting. For example, the studies of Van Gerven and Armelagos (1983) and Mensforth (1990) both attempt to demonstrate differences in the age structure between the estimated target sample and known-age reference method distribution as evidence for their independence. However, the exact ages-at-death for the archaeological samples is unknown. Differences between reference and estimated target groups may exist for a number of other reasons, such as lack of correlation between the particular pubic symphysis methods used and true biological age, or inherent sample biases such as over- and under-representation of advanced-age adult groups.

The investigations of Lanphear (1989), Piontek and Weber (1990), Scheuer and Bowman (1995), Saunders et al. (1995), and Sirianni and Higgins (1995) tested the question of reference sample mimicry by comparing estimated cemetery (target) age structure against documented vital records as a method to validate the "true ages" of the cemetery sample distribution. However, these studies did not include comparisons of the reference sample age structure that was used to generate age-at-death estimates. For the most part, descriptions of reference methods and their respective reference samples are absent. In other cases reference methods are listed as "multifactorial," which is assumed to include a variety of aging techniques. As a result, no one reference age structure can be distinguished in order to test whether estimated target ages and documented true ages were either both similar or independent of the reference method sample distribution.

These methodological weaknesses were corrected for in a study done by Konigsberg and Frankenberg (1992) in which they used both mathematical and computer-simulated applications to investigate reference sample bias. The authors compared the age structure of the McKern and Stewart war dead with a simulated target sample drawn from a specified mortality profile. The age structure of the target group was simulated using a Monte Carlo procedure so that it differed substantially in age from the McKern and Stewart sample, although members of both groups were assumed to have aged in a similar manner. For each member in the target sample, a pubic symphysis stage was probabilistically assigned conditional on (simulated) age of the individual. The assigned symphyseal stages were then used to estimate an age-at-death distribution for the target sample. Estimates were produced using both a Bayesian method of probability that assigned individuals to each age category on the basis of the McKern and Stewart reference sample, and a maximum likelihood method of estimation (MLE) where information from the reference sample was used to obtain the target sample age distribution most likely to have produced the observed distribution of morphological stages conditional on age. Konigsberg and Frankenberg found that the traditional method of assigning individuals to age classes based on prior information from the reference sample, resulted in an estimated target age-at-death distribution that closely resembled the shape of the McKern and Stewart reference age structure. When the estimated age-at-death distribution was obtained by the MLE method, there was a much better fit between the estimated target age structure and the known-age target sample distribution.

Bocquet-Appel (1986, 1994) and Bocquet-Appel and Masset (1996) have also supported the use of a global probabilistic approach to age estimation and have strongly advocated the use of a uniform reference age-at-death distribution (equal representation at all ages) as a means to offset the influence of the a priori probability of age estimates carried in the reference sample.

III. The Statistical Development of Skeletal Age-at-Death Standards

There have been a number of different statistical methods used to estimate adult age-at-death from the pubic symphysis. Frequently and perhaps typically, the maturational changes of the pubic symphysis have been treated as interval data. Thus, most analyses have emphasized the practice of regressing age on phases of the pubic symphysis (Hanihara and Suzuki, 1978; Katz and Suchey, 1986; Nemeskéri et al., 1960; Sinha and Gupta, 1995; Snow, 1983). Other statistical approaches have included the fitting of normal distributions for age within phases (Jackes, 1985), or the explicit use of maximum likelihood estimation using both parametric methods (Boldsen, 1997; Skytthe and Boldsen, 1993) and nonparametric methods (Konigsberg and Frankenberg, 1992).

The most common approach to estimating adult age-at-death standards from the pubic symphysis has been based on a model of regressing age on morphological phase (Hanihara and Suzuki, 1978; Katz and Suchey, 1986; Nemeskéri et al., 1960; Sinha and Gupta, 1995; Snow, 1983). In this context, the standards used to assign estimated age-at-death are based on referred observations from a known-age distribution of phases in a reference skeletal sample. The premise of this model can be particularly problematic for use with adult age-at-death estimation. If we assume that age is dependent on phase, then the model suggests that the maturational changes in the pubic symphysis cause aging, rather than in fact, that age causes pubic symphysis maturation. Furthermore, because the standards for the estimate of age-at-death must rely on the age distribution in the reference sample, an unbiased estimate of age-at-death conditional on the observed phases can only be produced if the age-at-death structure of the target and reference samples are equal, or if the skeletal indicator is perfectly correlated with age (Konigsberg and Frankenberg, 1992). However, it is well known that there are few skeletal indicators that are even at best correlated at the 0.80 level (Buikstra and Konigsberg, 1985). If the correlation is less than one, the estimate of the target sample mean age will be biased toward the reference sample mean age, and the estimated variance of age-at-death in the target sample will be too low (Konigsberg, Frankenberg, and Walker, 1997).

Jackes (1985) proposes the use of fitting normal distributions within symphyseal phases as a method for standardizing potentially uneven age distributions. Thus, for probabilities within ± 2 standard deviations, the assumption is made that estimates have accounted for 95% of all possible true ages for both males and females. Given that the distribution of age within a phase is dependent on the total age-at-death structure of the reference sample, Jackes' assumption of within-phase normal distributions is highly improbable and therefore impossible to estimate without bias.

Boldsen (1997), Konigsberg and Frankenberg (1992) and Skytthe and Boldsen (1993) support methods to establish a likelihood-based way of estimating skeletal age-at-death from the pubic symphysis. Maximum likelihood estimates have several desirable statistical qualities, including unbiasedness, efficiency, and normality (Agresti, 1996). With the use of maximum likelihood estimation, it is possible to consider the estimate of age-at-death when the morphological phase is dependent on age, rather than the opposite perspective (age conditional on phase) that is taken by the traditional approaches. As a result, this method is able to avoid the influence of the reference population in the construction of age-at-death standards. Thus, the estimate becomes the probability of being in a given symphyseal phase conditional on age $|P(\text{phase} \mid \text{age})|$.

Under this convention, the likelihood value for each distribution of the variable phase can then be found for all possible ages using well-known probability methods. That is, for a specific set of observations, which of all possible values of age-at-death is the most likely to have produced the observed phase data? The difference between the likelihood approach and the traditional model of regressing age conditional on phase, is that the assignment of age conditional on morphological phase is dependent upon the age structure of the reference sample distribution. However, with maximum likelihood estimation the target sample phase data can be substituted into a probability function, where the probability of the observed phases is a function of the unknown parameter of age-at-death.

CHAPTER 4

MATERIALS AND METHODS

I. Introduction

The "typological" scoring technique of the pubic symphysis (Todd and Suchey-Brooks systems) is based on assumed age-related morphological phases that appear during the natural process of adult skeletal maturation. The current study will present a statistical approach, using cumulative probit analysis, that is appropriate for summarizing the relationship of ordinal/categorical data on age. Secondly, the analysis will demonstrate a likelihood-based method in order to obtain the full posterior probability for age-at-death conditional on observed phases using both a maximum likelihood and Bayesian estimator. While the methodology for these approaches has existed in the statistical literature for decades, their application to the development of human skeletal age-at-death standards has remained largely unexplored.

II. Pubic Symphysis Data Sample

The skeletal data used in this study were generously made available by Dr. Judy M. Suchey in the form of her original pubic symphysis scores for 739 adult males. The sample data is taken from a large, well-documented collection of male pubic bones acquired through autopsy by Dr. Suchey at the Department of Chief Medical Examiner-Coroner, County of Los Angeles during the summer of 1977. The summary of the sample given here is taken from Suchey et al., (1986).

The males range in age between 14 to 92 years (Table 4.1). The causes of death for the sample include homicides, suicides, accidents, and unexpected natural deaths. The population is described as both socio-economically and occupationally diverse. It is known that these individuals were born throughout the United States and thirty-one foreign countries.

Table 4.1 *Los Angeles Sample of Male Pubic Bones: Age and Race* (Suchey et al. 1986)

	White	Black	Mexican	Oriental	Other
Age 14-19	45	16	14	2	4
Age 20-29	107	46	27	5	7
Age 30-39	69	30	19	1	1
Age 40-49	80	20	13	2	2
Age 50-59	73	19	5	2	2
Age 60-69	65	4	0	1	2
Age 70-79	38	3	0	2	2
Age 80-89	8	1	0	0	0
Age 90-92	1	1	0	0	0

All but four U.S. states (Alaska, Delaware, North Dakota and New Hampshire) have at least one sample representative. The most heavily represented states of birth are California (n=206) and Texas (n=42). The distribution for all North America (n=658) includes the U.S. (n=587), Mexico (n=69) and Canada (n=2). Males born outside of North America (n=55) are fairly evenly distributed among European, South American, and Asian countries.

The primary method for documentation of race focused on the "typological" physical appearance of the individual. Cases were classified by "race" using such features as skin color, hair color and form, nose and lip form, degree of prognathism, amount of body hair, and prominence of zygoma. Individuals were placed in four racial categories (White, Black, Mexican, or Oriental) with an "other" category for those cases considered ambiguous. The determination of race was also made from the death certificate, which included data on race, geographic origin of decedent and the decedent's parents.

The original number of total males autopsied for this study was approximately one thousand. However, individuals were deleted from the sample by Dr. Suchey if: [1] both pubic bones were not available; [2] pubic bones were not in good condition; [3] positive identification was never made on the individual; or [4] there were any questions regarding documentation for date of birth. As a result, the original total was reduced to the present size of 739 males.

The Los Angeles sample was originally examined (Katz and Suchey, 1986) using the Todd (1920) and the McKern and Stewart (1957) methods. The present study will include only the data for age and skeletal phase as defined by

Table 4.2 *Todd's Aging System Applied to the Los Angeles Sample* (Katz and Suchey, 1986)

Todd's Phases	Todd's Age Ranges	Los Angeles Sample Size	Los Angeles Ranges	Los Angeles Mean	Los Angeles Standard Deviation
I	18-19	19	14-19	16.68	1.46
II	20-21	50	14-23	18.12	1.74
III	22-24	52	17-24	20.38	1.90
IV	25-26	30	20-36	24.83	3.72
V	27-30	51	19-45	24.57	4.58
VI	30-35	43	22-51	28.81	5.89
VII	35-39	56	20-64	34.04	9.47
VIII	39-44	97	23-71	38.33	9.43
IX	45-50	241	21-87	51.00	13.64
X	50+	100	26-92	62.74	12.40

the Todd system. Table 4.2 compares the age ranges and skeletal phases assigned by Todd in his original sample with the distribution of ages and statistics generated by the application of Todd's method to the Los Angeles sample.

The Los Angeles statistics vary considerably from the original Todd age ranges. For example, the Los Angeles "means" fall below the lower end range for Todd phases I - VIII. In part, this demonstrates the tendency of the Todd method to "overage" individuals. It may also be of interest to note within the Los Angeles sample that the "oldest" patterns, phases IX - X, can occur in males in their twenties.

For the present study, the Los Angeles sample was collapsed into three modified distributions representing five-, six, and seven-phase scorings that were compared with the original ten-phase system (Table 4.3). The purpose for adjusting the number of phases was to evaluate whether or not collapsing the distributions by phase would improve the precision of the maximum likelihood or Bayesian estimate of the probability of age-at-death; the expectation being that all things considered equal, the wider the phase range the lower the number of misestimated individuals.

Table 4.3 *Distribution Differences for the Phase Grouping Comparison*

Ten-phase		Seven -phase		Six-phase		Five-phase	
I	19	I, II, III	121	I, II, III	121	I, II, III	121
II	50	IV, V	81	IV, V	81	IV, V, VI	124
III	52	VI	43	VI	43	VII, VIII	153
IV	30	VII	56	VII, VIII	153	IX	241
V	51	VIII	97	IX	241	X	100
VI	43	IX	241	X	100		
VII	56	X	100				
VIII	97						
IX	241						
X	100						

III. <u>Mortality Reference Samples</u>

To establish an age-at-death reference structure, mortality data were obtained from two external sources. Injury mortality samples were taken from prepared data tables posted by the National Center for Health Statistics (NCHS) via their on-line Internet public health information system known as "CDC WONDER" (http://wonder.cdc.gov/>)[1997], and skeletal age-at-death data were obtained for the Terry Collection from Dr. David Hunt, Collection Manager of the Physical Anthropology Division, Department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington, D.C.

NCHS injury mortality data were selected for U.S. adult males, all races, 15 - 85+ years, for the period of 1989-1994 (Table 4.4).

Table 4.4 *NCHS Injury Mortality Data for the Period 1989-1994*

age	Homicides	Suicides	Motor Vehicle Accidents	Unintentional Drowning	Flame/Fire
15-19	16400	9651	21986	2355	384
20-24	22471	15153	27354	2197	637
25-29	18559	15462	20977	2114	820
30-34	15701	16192	18418	2144	1019
35-39	11922	14885	14585	1722	958
40-44	8328	12609	11265	1372	882
45-49	5449	9860	8673	975	717
50-54	3612	8028	6888	756	659
55-59	2500	7231	5935	690	649
60-64	2114	7315	5774	644	858
65-69	1571	7394	5536	606	859
70-74	1130	7450	5424	506	797
75-79	773	6969	5264	389	821
80-84	468	5065	4283	264	689
85+	343	3605	3165	242	740

A total of 5 different injury mortality distributions were chosen in order to examine how individual causes of death can contribute to differences in age-specific mortality schedules (Preston et al. 1972; Preston 1976). The categories included death by homicide, suicide, flame/fire, unintentional drowning, and by motor vehicle accident.

Age-at-death data from the Terry Collection represents a large sample (n=1663) of predominantly American Black and White males (n=988) and females (n=675) aged from 14 - 102 years (Table 4.5). Five of the individuals from the male sample are documented as Asian and one as Mexican-American. The causes of death are recorded for nearly all individuals and include a variety of chronic and acute conditions particularly involving heart, lung, kidney and liver disease.

Table 4.5 *Age-at-Death Data for the Terry Collection Sample*

	males			females		
age	black	white	other	black	white	other
14-19	6	2	0	7	1	0
20-24	28	2	0	22	1	0
25-29	43	6	0	27	2	0
30-34	54	9	2	21	7	0
35-39	55	18	0	37	6	0
40-44	57	29	1	34	11	0
45-49	53	41	0	27	12	0
50-54	53	46	0	37	28	0
55-59	47	52	1	28	26	0
60-64	51	65	1	27	38	0
65-69	34	71	0	23	43	0
70-74	21	57	0	26	43	0
75-79	15	36	0	18	35	0
80-84	6	13	1	20	35	0
85+	7	5	0	15	18	0

The osteological collection, which was organized in the late 1910's by anatomist Dr. Robert J. Terry, consists primarily of indigents or those whose bodies had become the property of the State when no family members had claimed the decedents after death. Morgue records indicate that sample members were born during the period from 1840 to 1924. The cadavers were primarily collected from hospital morgues and institutions in St. Louis, although a few individuals came from other locations in Missouri (Hunt, 1997).

IV. Analytical Model

By assuming that the ages of transition between ordered phases follow a normal distribution, a cumulative probit can be applied to the Suchey data to find a mean and standard deviation for the ages of transition between morphological phases. The model takes the form of a cumulative probit regression with k parameters, where k represents the number of phases. The first k-1 parameters are constants that represent the thresholds, or cutpoints, at which the transitions are made from one phase to the next higher. The k^{th} parameter is the regression on age. From these parameters, it is possible to find the mean ages-at-transition between phases and a common variance for the age of each transition. Preliminary analyses on the Suchey data demonstrate that the variances do increase with age. Therefore, the current study also includes two additional models for comparison. Anderson's "stereotype" model (1984) produces a set of score parameters that can be identified by individual mean estimates of age and standard deviations for each phase. The third model is one in which age is measured on a logarithmic scale in order to account for the increasing variance while still maintaining an ordinary cumulative probit model analysis (Clogg and Shihadeh, 1994).

From the cumulative probit analysis, Bayes' probability theorem can be applied to estimate the posterior density of age for an individual skeleton conditional on the observed symphyseal phase. Thus, we can either obtain a maximum likelihood posterior distribution for age-at-death conditional on phase, or we can use an informative prior for age to obtain the Bayesian density. For the maximum likelihood estimate, the prior density for age is treated as a uniform prior such that the posterior density is proportional to the likelihood of the phase conditional on age. For the Bayesian estimator, the external reference mortality data is taken as the informative prior for age-at-death and incorporated into finding the posterior density.

Bayes' Theorem can be used so that the *posterior probability* that an individual is a particular age conditional on the observed phase, is proportional to the *prior probability* that the individual is that given age multiplied by the probability that an individual of that given age would be in the observed symphyseal phase. For example, the posterior probability that an individual in phase II would be exactly 25 years old is:

$$P(\text{age } 25 \mid \text{phase II}) \propto P(\text{phase II} \mid \text{age } 25)\ P(\text{age } 25). \qquad (1)$$

posterior probability **likelihood** **prior probability**

A full probability model connecting across all possible ages of estimation can be expanded to:

$$\textbf{\textit{P (age 25| phase II)}} = \frac{\textbf{\textit{P (phase II|age 25) P (age 25)}}}{\sum_{age=1}^{120} \textbf{\textit{P (phase II | all ages) P (ages)}}} \tag{2}$$

The Bayesian paradigm combines three important concepts in probability theory: *prior probability*, *likelihood*, and *posterior probability* (Gelman, Carlin, Stern, and Rubin, 1995). The *prior probability* is based on one's belief or prior knowledge of a hypothesis being true before experimental evidence is demonstrated. In this example, it would be the a priori age distribution for a particular case given no other outside information. Usually, for a single forensic skeleton the prior distribution for age is flat or uninformative, unless we have some prior knowledge about the expected age-at-death distribution that we believe represents the particular manner of death. For example, this prior knowledge may be the age-at-death distribution for death by homicide or the age-at-death distribution for death by drowning.

The *likelihood* is the conditional probability of the observed evidence given that the hypothesis about the evidence is true. For example, this would be the probability that an individual is in phase II (the observed evidence) given that the individual is age 25 (the hypothesis).

Finally, the outcome or *posterior probability* is the conditional probability of a hypothesis being true given the value of the observed evidence. This is the probability of an individual being age 25 years after taking into consideration both prior information from a reference distribution and the observed morphological phase evidence. The constant of proportionality is given by the reciprocal of the sum over all age categories of the product of the corresponding prior probabilities and likelihoods (as seen in the denominator of equation (2)). The only assumption made by this model is that the target and reference samples age in the same manner. The distribution of age for the reference sample is not superimposed on the target sample.

V. Analytical Methods

Because the specified models used in this study are often computationally demanding, the analysis has been carried out using specialized computer software written by Dr. Lyle Konigsberg. The software application, called *"PHASES,"* consists of 3 FORTRAN programs (*phases*, *mleage*, and *bayage*) designed specifically for the univariate estimation of adult skeletal age-at-death using ordinal/categorical data (this application is made available at <http://konig.la.utk.edu/phases.html> [1997]).

a. *Phases* Program

The *phases* program is used to find the maximum likelihood estimates for the ages of transition between the (ordered) phases of pubic metamorphosis.

The model that is fit to the data assumes that the ages of transition between the phases are normally distributed, such that the distribution for each transition is characterized by a mean and standard deviation. For example, with a six-phase system there are five transitions (from I to II, II to III, III to IV, IV to V, and V to VI).

Within the *phases* program there are three types of cumulative probit models that can be used to fit the age and phase data: (1) a standard cumulative probit; (2) a cumulative probit with age measured in log scale; and (3) a "stereotype" cumulative probit model. These models are described in Agresti (1996), Aitchison and Silvey (1957), Anderson (1984), and Long (1997). An important and implicit assumption for all three of the *phases* probit models is that the means are ordered sequentially by category, such that the mean age of transition from phase I to II is lower than from phase II to III, which is lower than III to IV and so on. Therefore, the probability that an individual is, for example, in phase IV, is the difference between the probability of being in phase IV or greater and being in phase V or greater. For this reason the models are defined as "cumulative."

The *phases* program allows for some changes from the standard computation of the cumulative probit. For example, the standard cumulative probit integrates normals beginning from negative infinity or ending at positive infinity. *Phases* allows for truncation ages to be set on the first and last ordered phases. This results in a better fitting model for use with adult skeletal indicator data such as the pubic symphysis. Specifically, the lack of setting a lower truncation age limit could result in the (unlikely) possibility of passing from phase I to phase II during early childhood or even at a "negative" age. However, setting the lower truncation age too high and too close to the onset of puberty is also problematic. A lower age limit that is truncated too "high" could compress the age distribution for the transition of the first to the second phase and result in defining a lower limit for the transition that is biased. The same effect would be true for setting the upper truncation age too low, which again would curtail the distribution and misrepresent the upper boundary for the transition to the last phase. To offset these potential problems in the current analysis, the truncation ages have been set at "1" and "120" years.

There are also some minor differences in output between the three probit models used in the *phases* program. In the standard and log scale cumulative probit models, all standard deviations are taken as equal. In a six phase system, this would result in five means and only one common standard deviation. The condition of generating one common standard deviation for all phases may be a difficult assumption to justify considering the relatively high degree of heterogeneity noted in advanced patterns of human aging (Brant and Pearson, 1994).

With the "stereotype" cumulative probit model, a standard deviation is generated for each of the transitions between phases, which in the six-phase system would result in five means and five standard deviations. The stereotype model can be problematic, however, and has demonstrated some difficulties in estimating the transitions for earlier age classes and phases. The problem occurs if the initial thresholds for each phase and distribution are overlapped and as such not properly ordered. This can result in the calculation of negative cumulative probabilities, which the program then resets to zero. This problem can be resolved by simply collapsing two or more adjacent phases into one phase.

b. *Mleage* Program

The *mleage* program uses the output generated from the *phases* program and creates a file with the maximum likelihood posterior probabilities for age conditional on being in each phase of symphyseal metamorphosis. In Bayesian terms, the posterior probabilities estimated by *mleage* are based on an "uninformative" prior for age. This procedure would be comparable to estimating age based on a "uniform" distribution, as advocated by Bocquet-Appel (1986, 1994) and Bocquet-Appel and Masset (1996), in order to avoid the relationship between the target sample estimates and the reference age-at-death structure.

c. *Bayage* Program and the Siler Hazard Model

The *bayage* program estimates the (Bayesian) posterior probabilities for age-at-death based on *a priori* information taken from an external reference mortality distribution. For the current study, the reference data was taken from injury mortality tables prepared by the National Center for Health Statistics (NCHS), as well as documented skeletal ages-at-death from the Terry Collection.

To calculate the probability density function, each reference sample was fit using a truncated 3-component Siler hazard model (Gage, 1989; Gage and Mode; 1993). The standard Siler model includes three biological components that correspond to the hazard of mortality throughout the human life span. The first component, infant mortality, is the value of the hazard of death at birth and denotes the rate at which the hazard is reduced with age. The second component, the constant overall hazard of mortality, represents deaths that occur randomly with respect to age. The third component, senescent mortality, is the rate of increase of the hazard of death with advancing age (Gage, 1991; Wood, Holman, Weiss, Buchanan and LaFor, 1992). For the purpose of this study, the Siler model was truncated by reducing the "infant mortality" component ($a_1 b_1$) to zero, thus abbreviating the model to a Gompertz-Makeham probability density function using the constant and the senescent (a_2, a_3b_3) mortality hazards. The Siler model was fit with starting parameter values using

CHAPTER 5

RESULTS

I. Siler Model Parameter Values and Reference Distributions

The Siler model parameter values for the overall constant (a_2) and senescent mortality components (a_3, b_3), using the reference data from the NCHS injury mortality samples and the Terry Collection are shown in Table 5.1. Parameter values for the Suchey data were included for comparison. The Siler parameter values are also presented graphically (Figures 5.1 -5.6) as probability density distributions and age-specific hazards of death. The initial hazard rates generated by the Siler model were converted to probabilities using a formula from Wood et. al (1992, pg. 46). The probability density functions were used as the informative (prior) distributions for age-at-death leading to the Bayesian estimator.

The probability density function and age-specific probability of death for the NCHS injury mortality samples are shown in Figures 5.1 - 5.2. The probability densities (Figure 5.1) are more or less concave for homicides, motor vehicle accidents, suicides, and unintentional drownings. The concave pattern is characteristic of high mortality among young and mid-life adults, with an early and rapid decline between the ages of approximately 15 - 40 years. In contrast with the other NCHS samples, the density of deaths by flame-fire is relatively

Table 5.1 *Siler Parameter Components for the References Samples and the Suchey Data Set*

male homicide 1989-1994	**a2** 0.0048 **s.e.** 0.0055	**a3** 0.0396 **s.e.** 0.0053	**b3** 0.0183 **s.e.** 0.0017
male suicide 1989-1994	**a2** 0.0235 **s.e.** 0.0002	**a3** 0.0008 **s.e.** <0.0001	**b3** 0.0744 **s.e.** 0.0009
male mv accident 1989-1994	**a2** 0.0381 **s.e.** <0.0001	**a3** <0.0001 **s.e.** <0.0001	**b3** 0.1271 **s.e.** 0.0011
male unintentional drowning 1989-1994	**a2** 0.0356 **s.e.** 0.0006	**a3** 0.0009 **s.e.** 0.0002	**b3** 0.0714 **s.e.** 0.0040
male flame-fire 1989-1994	**a2** 0.0126 **s.e.** 0.0005	**a3** 0.0011 **s.e.** 0.0002	**b3** 0.0679 **s.e.** 0.0024
Terry Collection	**a2** <0.0001 **s.e.** 0.0014	**a3** 0.0043 **s.e.** 0.0007	**b3** 0.0540 **s.e.** 0.0029
Suchey Data	**a2** 0.0232 **s.e.** 0.0033	**a3** 0.0027 **s.e.** 0.0015	**b3** 0.0616 **s.e.** 0.0096

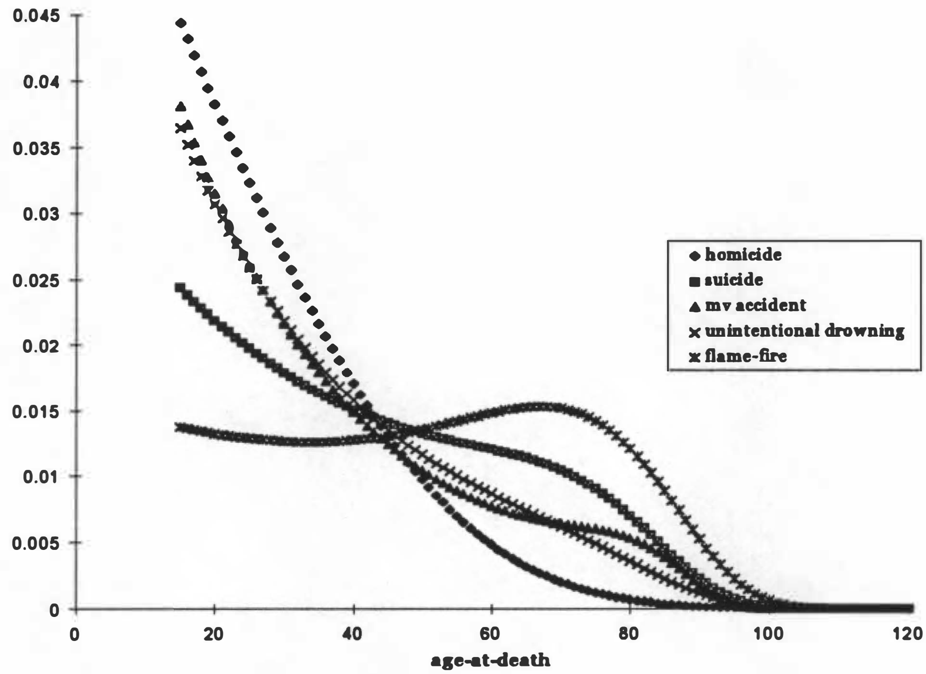

Figure 5.1 Probability Density Distributions for NCHS Injury Mortality Samples.

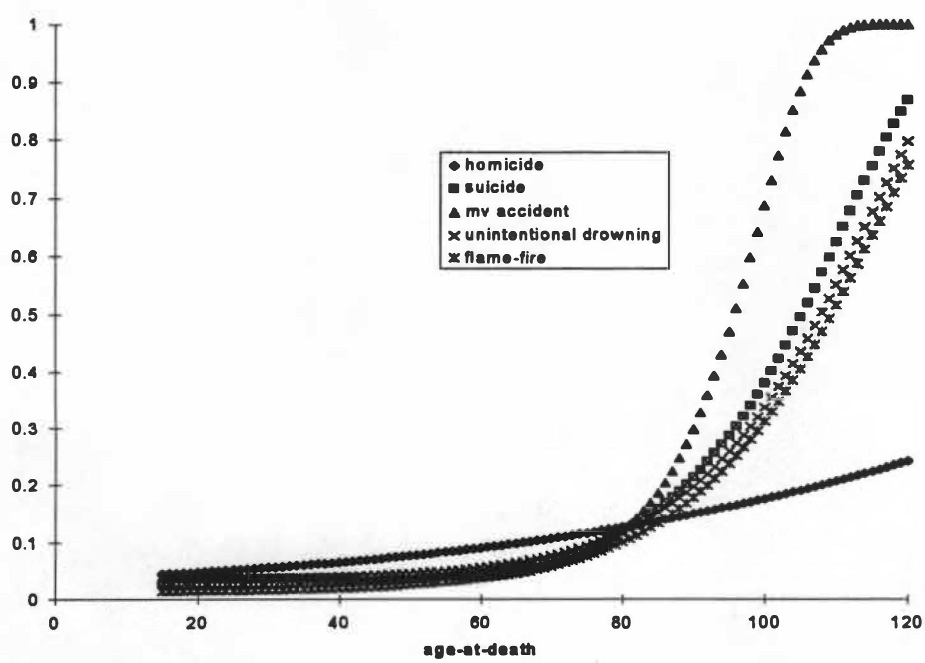

Figure 5.2 Age-Specific Probability of Death for NCHS Injury Mortality Samples.

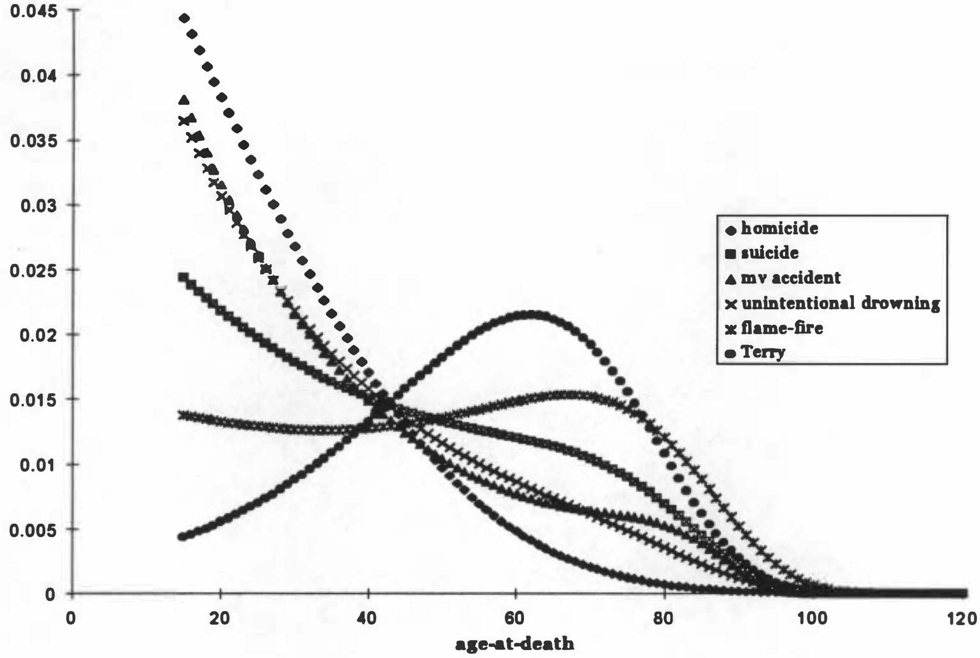

Figure 5.3 Probability Density Distributions for NCHS Injury Mortality Samples and Terry Collection.

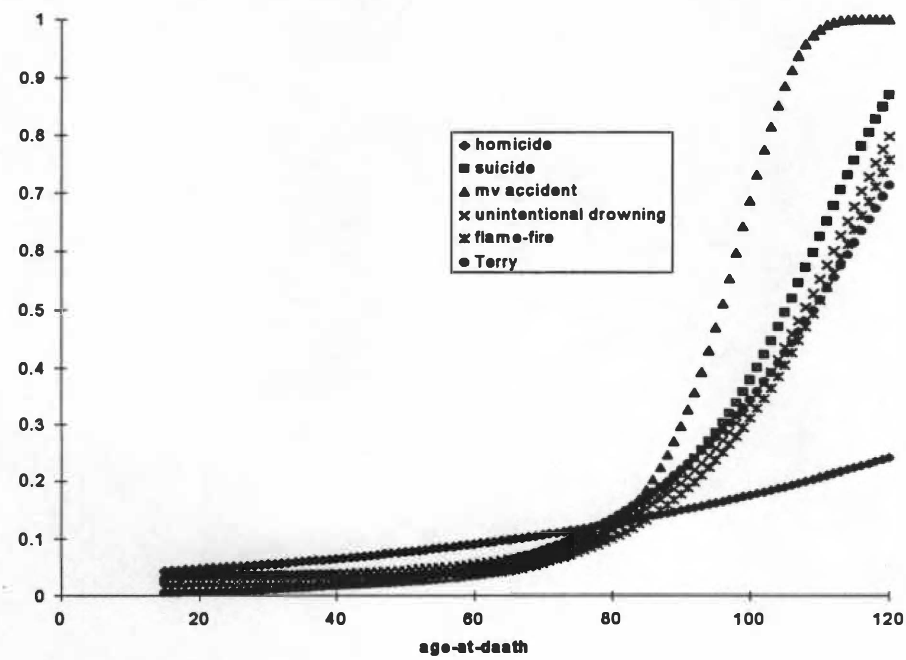

Figure 5.4 Age-Specific Probability of Death for NCHS Injury Mortality Samples and Terry Collection.

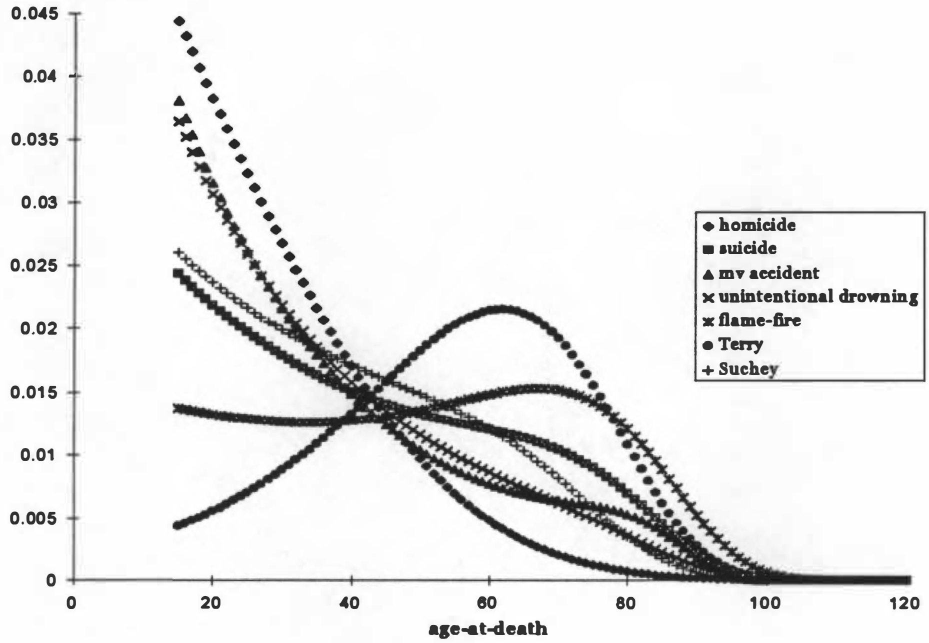

Figure 5.5 Probability Density Distributions for NCHS Injury Mortality Samples, Terry Collection, and Suchey Data Sample.

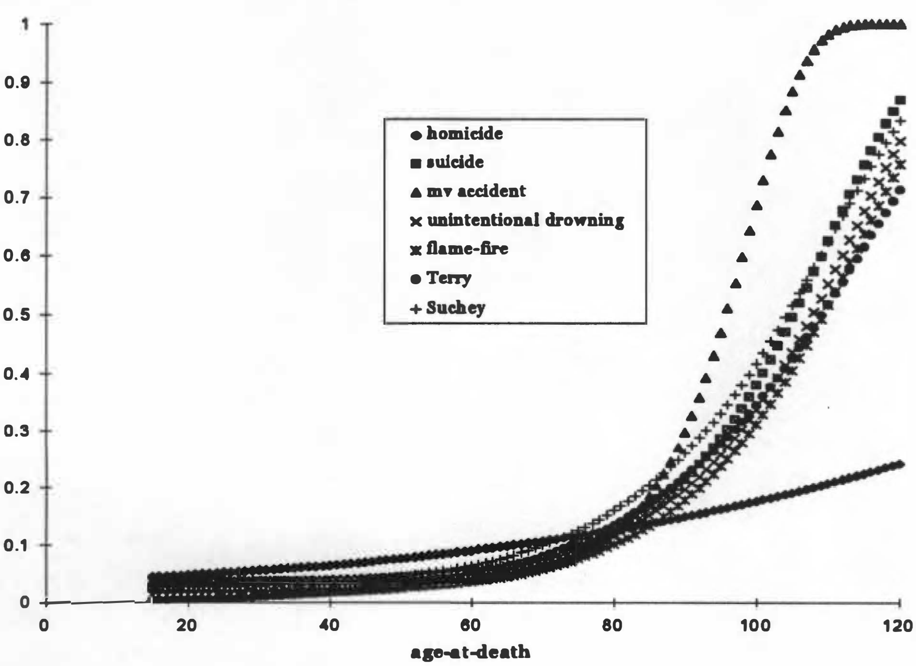

Figure 5.6 Age-Specific Probability of Death for NCHS Injury Mortality Samples, Terry Collection, and Suchey Data Sample.

constant between 15 - 80 years. Death by flame-fire is also the lowest of the injury mortality probabilities up to about the fifth decade. By 50 years of age, the probability of death by flame-fire increases slightly, and begins to demonstrate a higher density of deaths compared with the other NCHS distributions.

With respect to age-specific probabilities of death (Figure 5.2) for the mortalities during the late senescent period. Of the five causes of death, the most significant increase and greatest risk of death comes from motor vehicle accidents. In comparison, the probability of death by homicide maintains the lowest and most consistent risk of death for the injury mortality profiles throughout the entire adult lifespan.

Significant pattern differences exist in probability density distributions between the NCHS injury mortalities and the Terry Collection sample (Figures 5.3 and 5.4). In the Terry Collection, the distribution of mortality (Figure 5.3) is characterized by a broad and inverted "u-shaped" curve. This pattern indicates a greater density of older-aged decedents in the skeletal sample with the highest probability of deaths occurring at approximately 60 years of age. These differences between the Terry Collection and NCHS profiles are generally expected due to the greater proportion of older-aged individuals that typically compose cadaver collections. Because documented skeletal collections frequently come from anatomical dissecting rooms, a major obstacle inherently exists in obtaining reference skeletal samples that are representative of the varied patterns of mortality by age, sex, race, and manner of death.

In Figure 5.4, the age-specific probability of death for the Terry Collection appears to follow the same senescent pattern of risk as that seen for several of the NCHS samples (suicide, unintentional drowning, flame-fire). Again this pattern would be interpreted to suggest that the risk of mortality increases with advancing age in the senescent phase of life.

Figures 5.5 and 5.6 compare the previous probability density distributions and age-specific probability of death for the NCHS profiles and the Terry Collection, with the Suchey data sample. Probability densities and age-specific risks of mortality for the Suchey sample are similar to the distribution for death by suicide. The greatest density of deaths occurs from young to mid-adulthood, with a substantial increase in the probability of death during the last decades in the late senescent period.

II. Mean Age of Transition Between Phases in the Suchey Sample

The maximum likelihood estimates of the mean age and standard deviation of the transition between the ordered phases in the Suchey data sample are shown in Tables 5.2 and 5.3. Estimates are presented for each of the phase groupings based on all of the cumulative probit models.

The mean age and standard deviation of the transition between phases is roughly identical in all four phase groupings. The differences seen in the age-at-transition for the first two phases of the ten-phase distributions (particularly

Table 5.2 *Estimated Mean Age of Transition Between Phases: Five- and Six-Phase Samples*

‡ The following cumulative probit models were fit with truncation ages at 1.0 - 120.0

	5 Phase Cumulative Probit		5 Phase Stereotype Probit		5 Phase Cumulative Log Age Probit	
	mean age of transition	*std. error*	*mean age of transition*	*std. error*	*mean age of transition*	*std. error*
1-2	19.12	0.7189	21.15	0.1518	3.02	0.0186
2-3	29.75	0.6601	28.47	0.4898	3.35	0.0172
3-4	41.71	0.6907	40.64	0.7722	3.68	0.0165
4-5	64.29	0.8940	69.31	1.87	4.18	0.0206
	std. dev.	*std. error*	*std. dev.*	*std. error*	*std. dev.*	*std. error*
	10.33	0.3937	2.09	0.2251	0.2452	0.0098
			6.56	0.5170		
			11.82	0.8068		
			18.14	1.64		

Ln(LK) = -766.7279 Ln(LK) = -645.0021 Ln(LK) = -684.9419

	6 Phase Cumulative Probit		6 Phase Stereotype Probit		6 Phase Cumulative Log Age Probit	
	mean age of transition	*std. error*	*mean age of transition*	*std. error*	*mean age of transition*	*std. error*
1-2	19.05	0.6780	21.06	0.0191	3.02	0.0160
2-3	26.23	0.5846	25.61	0.3089	3.25	0.0126
3-4	29.85	0.6939	28.41	0.5244	3.35	0.0178
4-5	41.71	0.6912	40.62	0.7773	3.68	0.0164
5-6	64.24	0.8874	69.32	1.8696	4.18	0.0204
	std. dev.	*std. error*	*std. dev.*	*std. error*	*std. dev.*	*std. error*
	10.24	0.3890	2.19	0.2294	0.2422	0.0095
			5.11	0.4311		
			6.64	0.5605		
			11.87	0.8223		
			18.16	0.6463		

Ln(LK) = -842.0185 Ln(LK) = -719.7057 Ln(LK) = -756.9534

Table 5.3 *Estimated Mean Age of Transition Between Phases: Seven- and Ten- Phase Samples*

‡ The following cumulative probit models were fit with truncation ages at 1.0 - 120.0

	7 Phase Cumulative Probit		**7 Phase Stereotype Probit**		**7 Phase Cumulative Log Age Probit**	
	mean age of transition	*std. error*	*mean age of transition*	*std. error*	*mean age of transition*	*std. error*
1-2	19.049	0.6712	20.99	0.0190	3.02	0.0160
2-3	26.24	0.5499	25.44	0.2584	3.25	0.0118
3-4	29.86	0.6001	28.42	0.4541	3.36	0.0132
4-5	34.35	0.6592	32.79	0.6420	3.48	0.0154
5-6	41.70	0.7184	40.63	0.7928	3.68	0.0172
6-7	64.25	0.8889	69.28	1.87	4.18	0.0205
	std. dev.	*std. error*	*std. dev.*	*std. error*	*std. dev.*	*std. error*
	10.26	0.3854	2.21	0.2296	0.2440	0.0093
			5.29	0.4525		
			7.44	0.6196		
			9.58	0.7015		
			11.66	0.8411		
			18.12	1.64		

Ln(LK) = -938.9035 | Ln(LK) = -821.7756 | Ln(LK) = -853.4868

	10 Phase Cumulative Probit		**10 Phase Stereotype Probit**		**10 Phase Cumulative Log Age Probit**	
	mean age of transition	*std. error*	*mean age of transition*	*std. error*	*mean age of transition*	*std. error*
1-2	6.41	0.8554	15.59	-	2.59	0.0270
2-3	13.87	0.7050	18.77	-	2.85	0.0154
3-4	19.29	0.5545	20.93	-	3.03	0.0107
4-5	22.01	0.6017	22.31	-	3.12	0.0137
5-6	26.33	0.5577	25.41	-	3.25	0.0117
6-7	29.92	0.6002	28.39	-	3.36	0.0130
7-8	34.37	0.6558	32.77	-	3.48	0.0152
8-9	41.66	0.7135	40.62	-	3.68	0.0170
9-10	64.17	0.8777	69.28	-	4.18	0.0210
	std. dev.	*std. error*	*std. dev.*	*std. error*	*std. dev.*	*std. error*
	10.12	0.3770	2.16	-	0.2396	0.0088
			1.87	-		
			2.21	-		
			5.04	-		
			5.30	-		
			7.45	-		
			9.60	-		
			11.68	-		
			18.12	-		

Ln(LK) = -1109.3380 | Ln(LK) = -967.2882 | Ln(LK) = -1013.4498 noticeable in the standard cumulative probit) are the result of effects from the lower limit truncation age fit to the model. These differences in the first two phases of the ten-phase sample are, however, directly absorbed in the collapsing of the five-, six-, and seven-phase groupings.

With respect to differences noted among the three cumulative probit models, the primary distinction is observed with the stereotype probit model. Samples fit with the stereotype probit generate a standard deviation for each of the transitions between phases. As a result, a lower standard deviation and standard error for the estimate of the age of transition can be seen in the earliest transitional phases. However, in general, the differences in the mean age of transition between phases for any of the three cumulative probit models are not markedly different.

III. Posterior Probability Distributions of Age-at-Death by Maximum Likelihood Estimator

The full posterior probability distributions for individual age-at-death conditional on phase are presented in Figures 5.7 - 5.10. The posterior probabilities were obtained by using the maximum likelihood estimator for all four phase groupings by each of the cumulative probit models used initially in the estimate of the mean ages of transition between phases.

Figures 5.7 - 5.10 compare the three probit estimation models for the five, six, seven and ten phase groupings. Within each of the cumulative probit

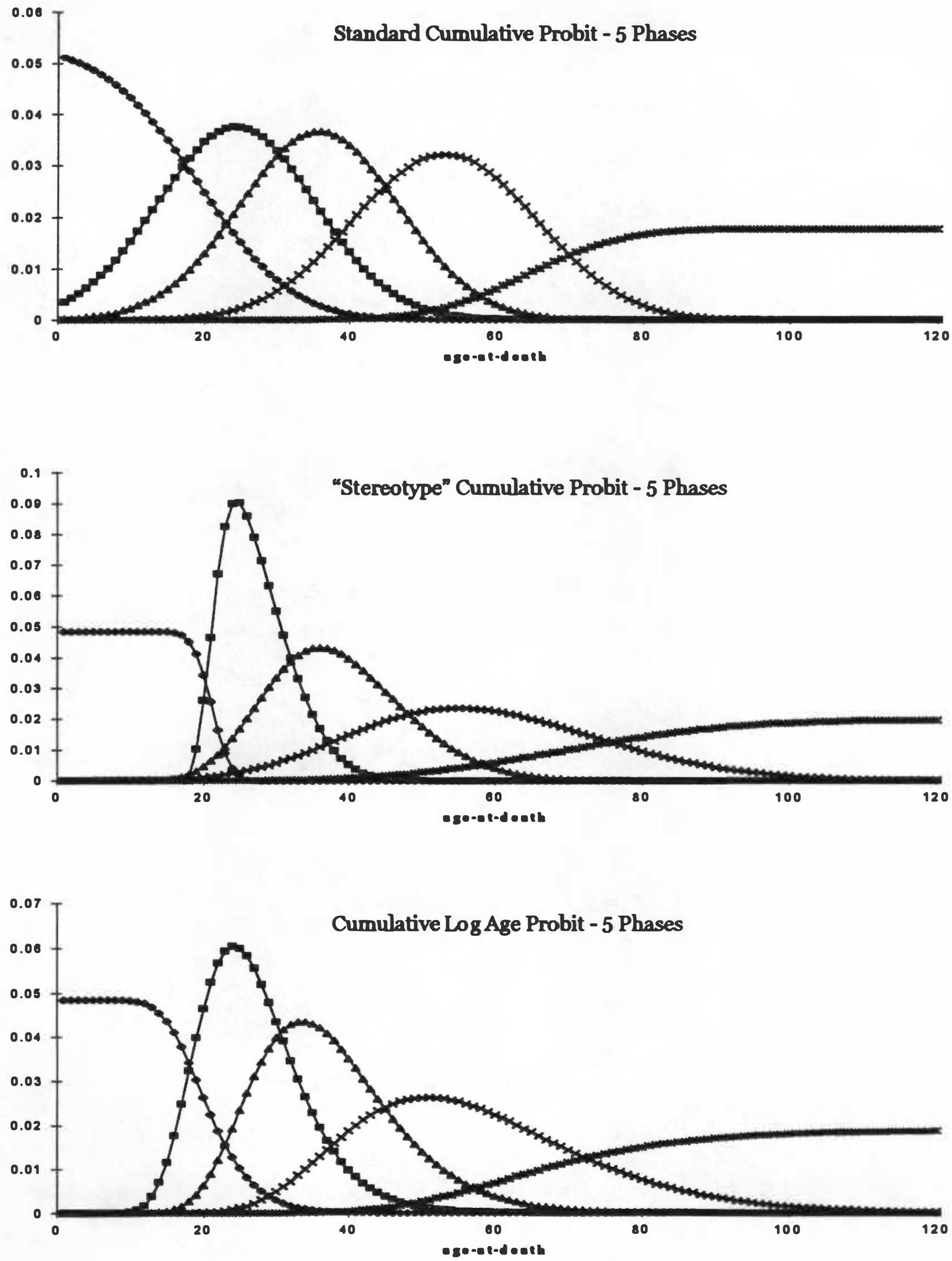

Figure 5.7 Full Posterior Distribution of Age-at-Death Conditional on Phase by Maximum Likelihood Estimator for Five Phase Sample Grouping.

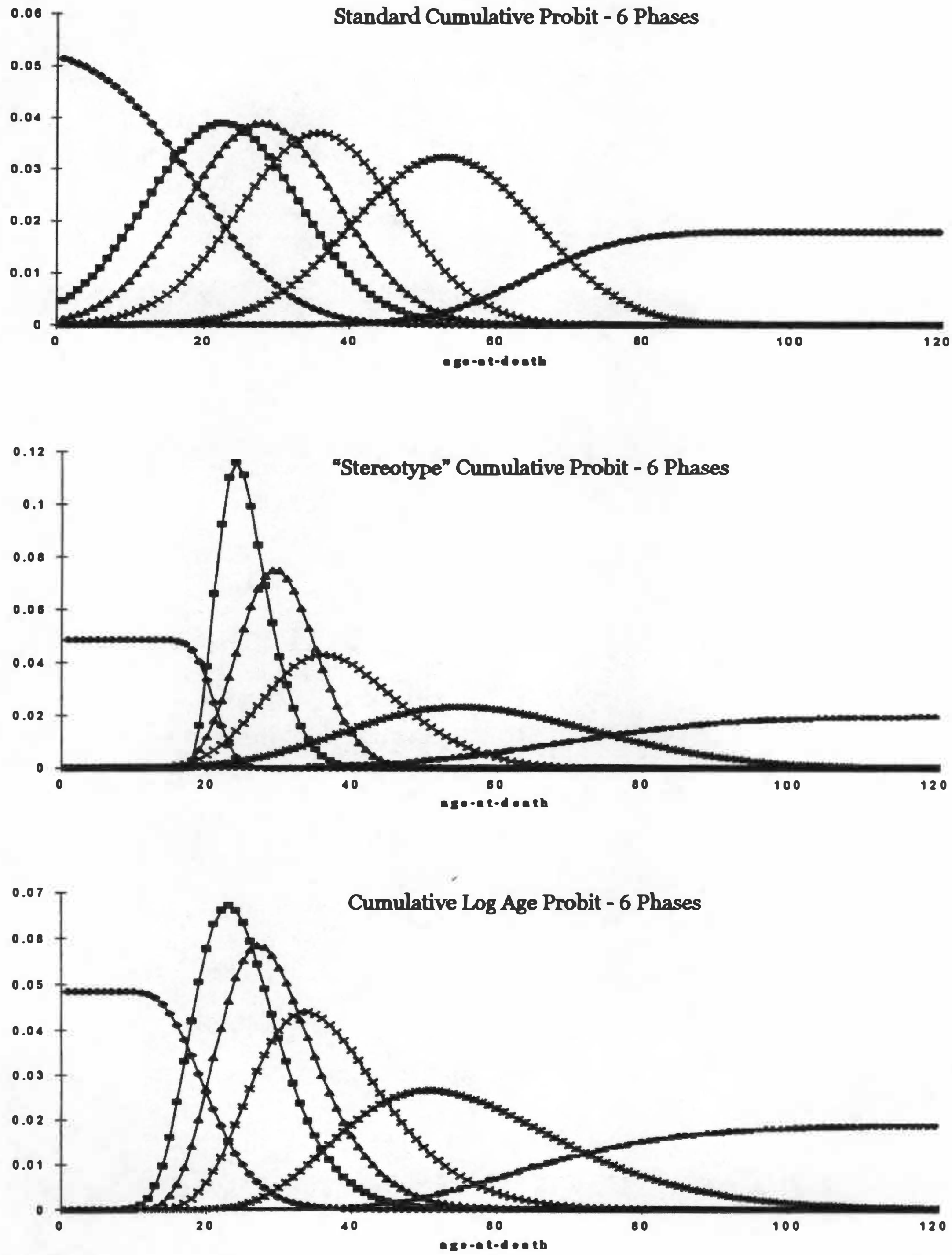

Figure 5.8 Full Posterior Distribution of Age-at-Death Conditional on Phase by Maximum Likelihood Estimator for Six Phase Sample Grouping.

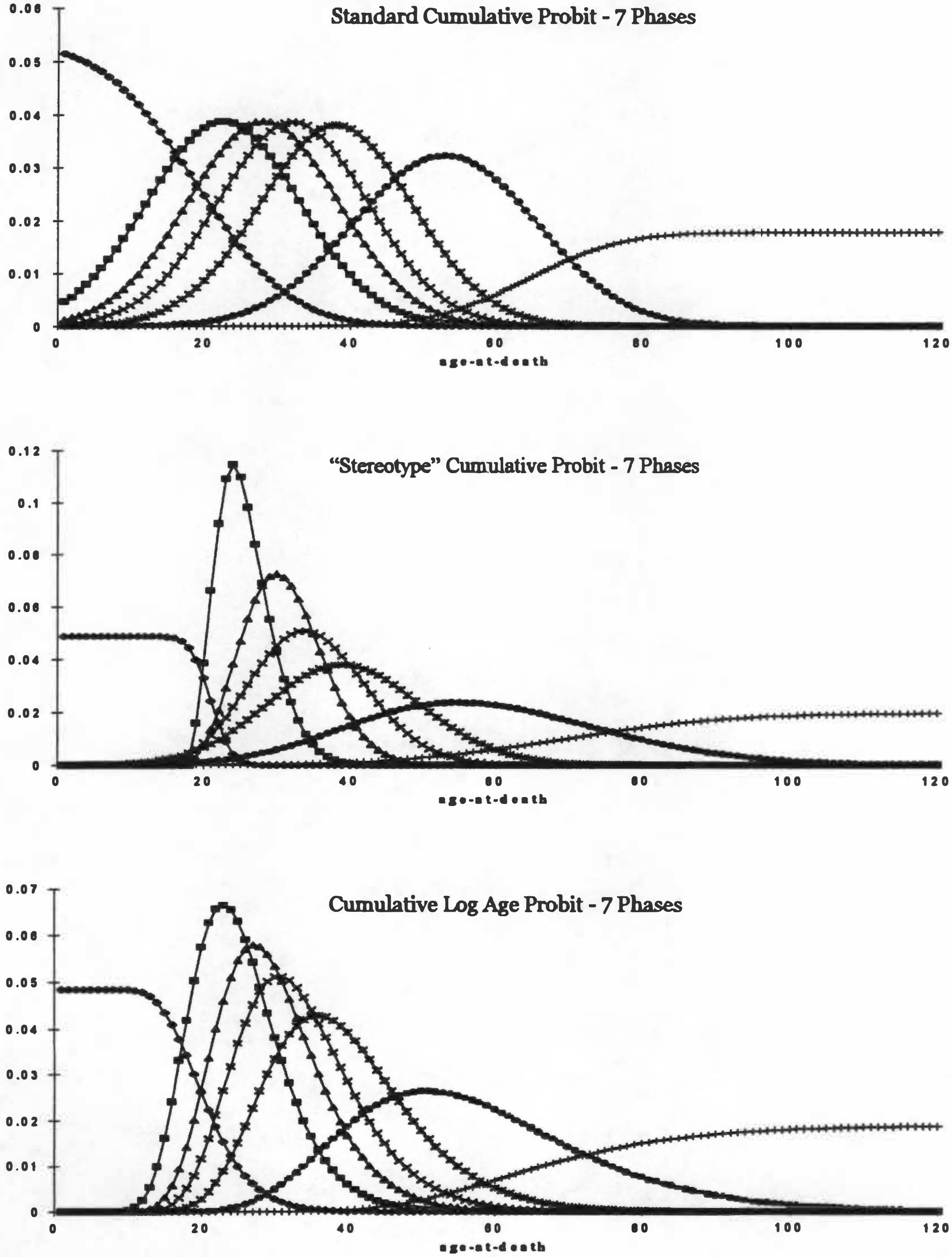

Figure 5.9 Full Posterior Distribution of Age-at-Death Conditional on Phase by Maximum Likelihood Estimator for Seven Phase Sample Grouping.

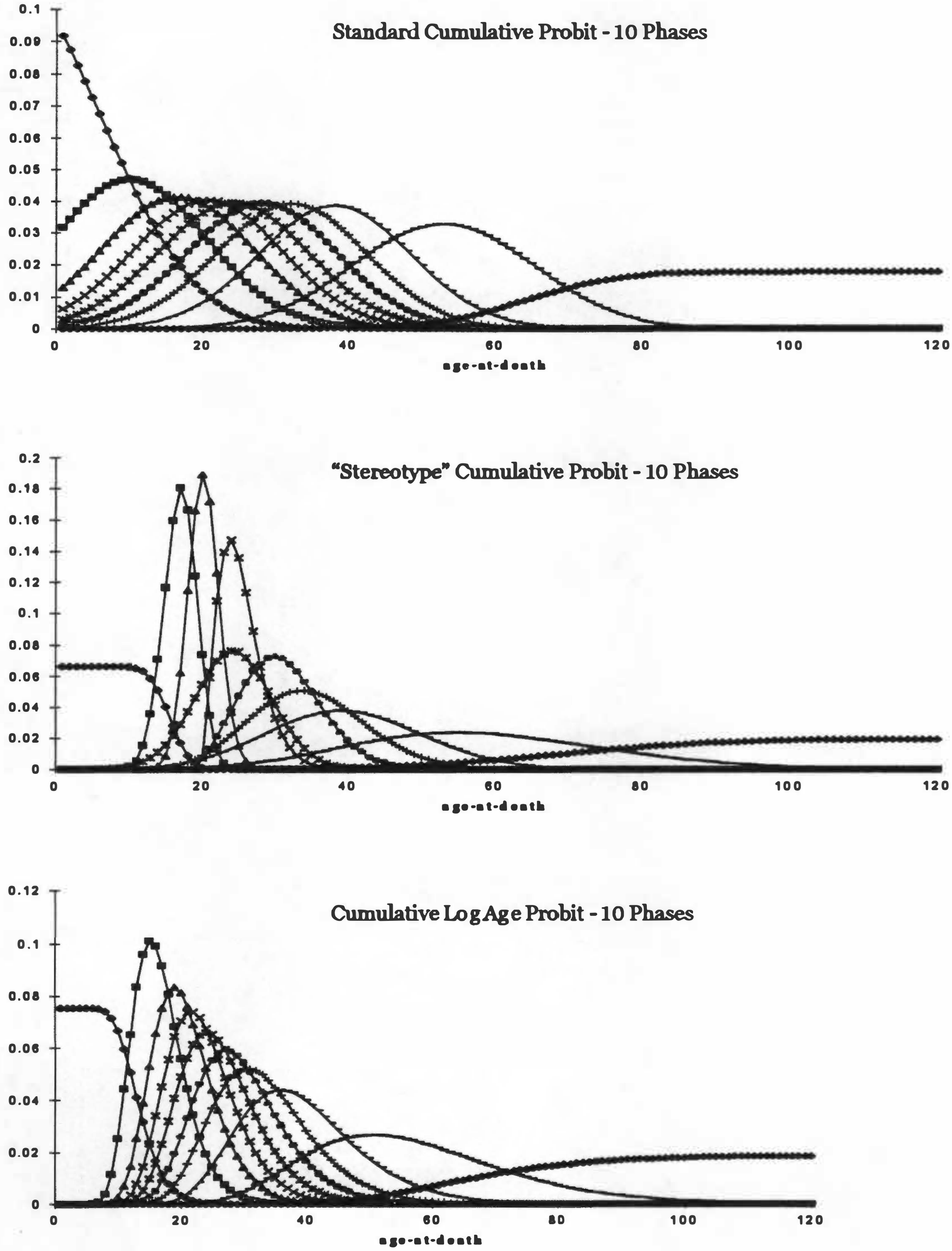

Figure 5.10 Full Posterior Distribution of Age-at-Death Conditional on Phase by Maximum Likelihood Estimator for Ten Phase Sample Grouping.

models, the curves from left to right show the posterior probability distributions of age-at-death conditional on being in a given morphological phase. While the actual patterns of the probability distributions remain similar in shape between each of the four phase sample groupings, the degree of overlap among phases (within groupings) increases substantially as the number of phases per sample increases (five, six, seven, and ten). In Figure 5.10, which shows the ten phase grouping, the lack of concentration and strong overlap among phases is especially evident in the second through ninth phases, which are almost entirely superimposed over one another in all of the estimation models.

Consequently, an overall comparison among all posterior probability distributions obtained by the maximum likelihood estimator suggests that a broad continuum of probable ages-at-death could have produced each of the morphological phases in the Suchey data. Any expectations regarding the improved precision or concentration of estimates of age-at-death due to fewer numbers of phases per sample were clearly not demonstrated from these results.

IV. Comparison of Bayesian and Maximum Likelihood Estimators

Tables 5.4 - 5.7 present the 95% highest posterior density for estimated individual age-at-death conditional on phase. Posterior densities are given for both the Bayesian estimators and maximum likelihood estimators used to analyze the Suchey sample. The density tables are organized by phase group and the associated cumulative probit model used in the initial estimate of the mean age

Table 5.4 *95% Highest Posterior Density for Estimated Age-at-Death in the Five Phase Group*

Standard Cumulative Probit Model for Five Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-31	15-32	15-31	15-31	15-33	14-37	1-32
2	15-39	15-41	15-39	15-40	16-43	16-46	5-45
3	17-47	18-52	17-49	18-50	19-54	23-56	14-57
4	26-62	30-70	28-69	28-68	33-72	36-71	29-75
5	46-85	53-89	52-88	51-89	56-92	54-87	56-118

"Stereotype" Cumulative Probit Model for Five Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-22	15-22	15-22	15-22	15-22	14-22	1-21
2	20-34	20-35	20-34	20-35	20-36	21-37	20-38
3	22-49	23-53	22-51	22-51	24-56	26-57	22-59
4	23-65	28-77	25-77	25-73	32-80	35-72	27-93
5	30-82	43-89	39-88	38-88	48-92	47-87	49-119

Cumulative Log Age Probit Model for Five Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-27	15-27	15-26	15-27	15-28	14-30	1-26
2	16-36	16-38	16-37	16-37	17-40	18-43	15-43
3	21-47	22-53	21-50	21-50	23-56	25-58	21-60
4	29-64	32-75	30-74	31-72	34-79	36-75	31-94
5	42-83	49-89	48-88	47-88	52-92	51-87	53-119

Table 5.5 *95% Highest Posterior Density for Estimated Age-at-Death in the Six Phase Group*

Standard Cumulative Probit Model for Six Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-31	15-32	15-31	15-31	15-33	14-36	1-32
2	15-37	15-39	15-37	15-38	15-41	16-44	4-43
3	16-41	16-43	16-42	16-42	16-45	18-48	8-48
4	17-47	18-52	17-49	18-50	19-54	23-56	14-56
5	26-62	30-70	28-69	28-67	33-72	36-71	29-76
6	46-85	53-89	52-88	51-89	56-92	54-87	56-118

"Stereotype" Cumulative Probit Model for Six Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-22	15-22	15-22	15-22	15-22	14-22	1-21
2	20-31	20-31	20-31	20-31	20-32	20-33	19-33
3	21-37	21-38	21-37	21-38	21-39	22-40	20-41
4	21-49	23-53	22-51	22-51	24-56	26-58	21-59
5	23-65	28-77	25-76	25-73	32-80	36-77	27-94
6	30-82	43-89	39-88	38-88	48-92	48-87	49-119

Cumulative Log Age Probit Model for Six Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-26	15-27	15-26	15-26	15-28	14-29	1-26
2	16-34	16-35	16-34	16-34	16-36	17-40	14-39
3	18-39	18-41	18-39	18-40	19-43	20-46	17-46
4	21-47	22-53	21-50	22-50	23-55	25-58	21-59
5	29-64	32-75	30-74	31-72	34-78	36-75	31-93
6	43-83	49-89	48-88	47-88	53-92	51-87	53-119

Table 5.6 *95% Highest Posterior Density for Estimated Age-at-Death in the Seven Phase Group*

Standard Cumulative Probit Model for Seven Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-31	15-32	15-31	15-31	15-33	14-36	1-32
2	15-37	15-39	15-37	15-37	15-41	16-44	4-43
3	16-41	16-43	16-42	16-41	17-45	18-48	8-48
4	16-44	17-47	16-45	17-44	18-49	20-52	12-52
5	19-49	20-53	19-51	19-48	21-55	25-57	17-58
6	26-62	30-70	28-69	26-57	33-72	36-71	29-76
7	46-85	53-89	52-88	41-66	56-92	54-87	56-119

"Stereotype" Cumulative Probit Model for Seven Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-22	15-22	15-22	15-22	15-22	14-22	1-21
2	20-31	20-32	20-31	20-31	20-32	20-23	19-34
3	22-38	22-40	22-39	21-39	22-40	23-42	21-42
4	20-44	21-46	20-45	21-45	22-48	24-50	20-50
5	20-50	21-55	20-53	20-53	23-57	26-59	19-60
6	23-65	28-77	25-77	26-73	32-80	36-77	27-93
7	30-82	43-89	38-88	38-88	48-92	47-87	49-119

Cumulative Log Age Probit Model for Seven Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-26	15-27	15-26	15-26	15-28	14-29	1-26
2	16-34	16-35	16-34	16-34	16-37	17-40	14-40
3	18-39	18-41	18-40	18-40	19-43	20-46	17-46
4	20-43	21-46	20-44	20-45	21-49	23-52	20-52
5	23-49	24-55	23-52	23-52	25-58	27-60	23-62
6	29-64	32-75	30-75	31-72	34-79	37-75	31-94
7	43-83	49-89	48-88	47-88	52-92	51-87	53-119

Table 5.7 *95% Highest Posterior Density for Estimated Age-at-Death in the Ten Phase Group*

Standard Cumulative Probit Model for Ten Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-26	15-27	15-26	15-26	15-27	14-29	1-23
2	15-30	15-30	15-30	15-30	15-31	14-34	1-31
3	15-33	15-34	15-33	15-33	15-35	14-39	2-36
4	15-35	15-37	15-35	15-36	15-38	15-42	3-40
5	15-38	15-40	15-38	15-38	15-41	16-45	5-44
6	16-41	16-43	16-41	16-42	16-45	18-48	8-48
7	16-44	17-47	16-45	17-45	18-49	20-52	12-52
8	19-49	20-53	19-51	19-51	21-55	25-57	17-58
9	26-42	31-70	28-69	28-67	33-72	36-71	29-76
10	46-85	53-89	52-88	51-89	56-92	54-87	56-119

"Stereotype" Cumulative Probit Model for Ten Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-18	15-18	15-18	15-18	15-18	14-18	1-16
2	15-20	15-20	15-20	15-20	15-20	14-20	12-21
3	16-23	16-23	16-23	16-23	16-23	16-24	16-24
4	21-30	21-30	21-30	21-30	21-30	21-31	20-32
5	16-31	16-32	16-32	16-32	16-32	17-34	14-34
6	22-38	22-40	22-39	22-39	22-40	23-42	21-42
7	20-44	21-46	20-45	20-45	22-48	24-50	20-50
8	20-50	21-55	20-53	20-53	22-57	26-59	19-60
9	23-65	28-77	25-77	26-73	32-80	36-77	27-94
10	30-82	43-89	39-88	38-88	48-92	47-87	49-119

Cumulative Log Age Probit Model for Ten Phases

phase	homicide	suicide	mv accident	drowning	flame-fire	Terry	*mleage*
1	15-21	15-21	15-21	15-21	15-21	14-21	1-17
2	15-24	15-25	15-24	15-24	15-25	14-26	9-26
3	15-28	15-29	15-28	15-29	15-30	15-32	12-32
4	15-32	16-33	15-32	15-32	16-34	16-36	14-36
5	16-35	17-36	16-35	16-36	17-38	18-41	15-41
6	18-39	18-41	18-39	18-40	19-43	20-46	17-46
7	20-43	21-46	20-44	20-45	21-48	23-51	20-52
8	23-49	24-55	23-52	23-52	25-58	27-59	23-61
9	29-64	32-75	31-74	31-71	34-78	36-75	31-93
10	43-84	50-89	48-88	47-88	52-92	51-87	53-119

of transition. Tables 5.4 - 5.6 show only minor differences between phase groups, which are based on modifications resulting from the collapsing of phases for the five-, six-, and seven-phase group distributions. These effects are clearly demonstrated in the comparison of the first three phases of the ten-phase sample (Table 5.7) , which have been collapsed into the initial phase in all other groupings.

Relatively few differences are detected between the 95% highest posterior densities obtained by either the maximum likelihood or Bayesian estimator. As in the maximum likelihood estimates, the Bayesian 95% highest posterior densities continue to show a considerable degree of overlap for estimated ages-at-death between phases. Most, if not all, of the specific numerical differences that do exist simply reflect the differences in the "lower end" truncation ages used to compute the *mleage* and *bayage* estimates.

Only slight differences can be noted for the 95% densities of estimated age-at-death by phase among the Bayesian estimators. Contrary to these results, it was expected that the variability for these estimates would be much greater based on the different causes of death in the prior reference distributions. To determine the extent to which any age-specific variation exists among the prior reference samples, a 95% confidence interval was computed.

Table 5.8 presents the confidence intervals for ages-at-death that account for 95% of the total deaths occurring in each of the reference sample

Table 5.8 95% Confidence Interval for Ages-at-Death Based on Reference Samples

Reference Sample	95% Confidence Interval for Ages-at-Death
NCHS - homicide	15 - 67
NCHS - suicide	16 - 86
NCHS - motor vehicle accident	15 - 85
NCHS - unintentional drowning	15 - 81
NCHS - flame-fire	16 - 91
Terry Collection	20-87
Suchey Sample	15 - 79

distributions. The Suchey sample is also included for comparison. Figure 5.11 demonstrates the same data graphically based on the survivorship function. Together, these results demonstrate that only minimal differences exist in ages-at-death between the age structures of the prior reference sample distributions. Therefore, the different causes of death represented in the prior distributions could not have affected significant differences between the 95% highest posterior densities for estimated age-at-death between the Bayesian estimators.

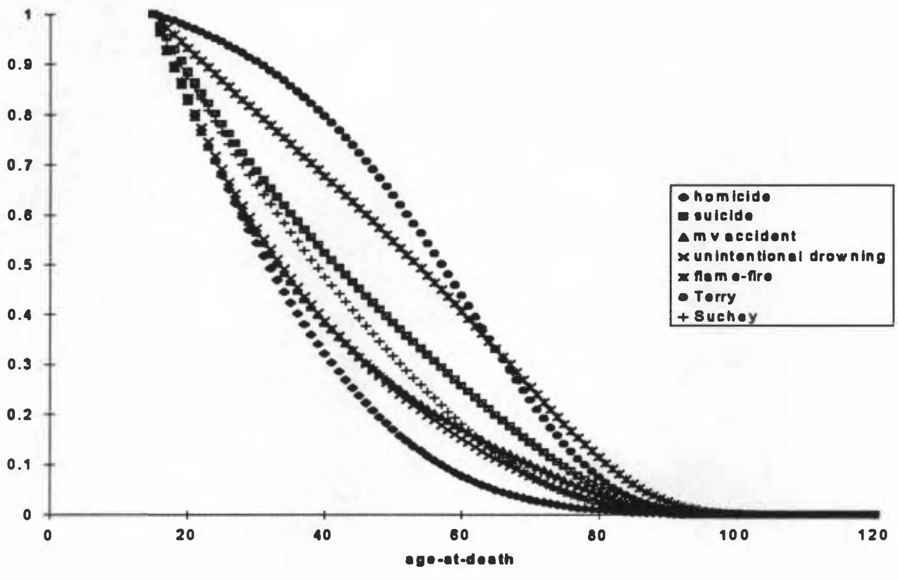

Figure 5.11 95% Confidence Interval for Ages-at-Death for the NCHS Injury Mortality Samples, Terry Collection, and the Suchey Data Sample.

A final overall comparison of the 95% highest posterior densities between the maximum likelihood and Bayesian estimators is useful in demonstrating the uniform and unbiased nature of the maximum likelihood function. The maximum likelihood obtains estimates of age-at-death based on a "uninformed" prior distribution. As such, the results of the 95% highest posterior density intervals produced by the maximum likelihood estimator present density distributions of age-at-death that include the majority of all age-phase densities generated by the Bayesian "informative" distributions.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Recent attention has focused on the problems of methodological error and bias in the estimation of adult skeletal ages-at-death. While in part the debate has generated the need for larger and more representative standard reference collections, the more cogent solution would be to concentrate on improving statistical methods such that the age structure of the reference sample would be largely irrelevant.

The estimation of skeletal age-at-death either by maximum likelihood or from a Bayesian estimator (where the prior distribution for age is external to the reference sample) will yield age estimates that are independent of the reference sample age-at-death distribution. To that end, the present study has re-analyzed the Suchey pubic symphysis data to obtain the estimated posterior probabilities of age-at-death that would have most likely produced the observed phase indicator.

A comparison of all posterior density distribution results for estimated age-at-death produced from each of the cumulative probit models by the maximum likelihood estimator, suggests that there is a wide array of probable ages-at-death that can produce a specified phase. This is particularly apparent in the case of estimating probabilities of age-at-death in later phases and older ages.

The course of aging during senescence appears to demonstrate a natural heterogeneity of metamorphic processes. As a result, it might be more compelling to conclude that as a skeletal indicator, the metamorphosis of the pubic symphysis is only weakly age-associated.

Comparing results of the 95% highest posterior densities between maximum likelihood and Bayesian estimators indicates that neither of the estimators were able to fit specified patterns of age-at-death with the Suchey pubic symphysis phase data. As a consequence of these results, it is suggested that the pubic symphysis should not be the only skeletal indicator used for the best estimate of adult age-at-death.

The reliability with which adult age-at-death can be estimated is affected by many factors. The estimation of adult skeletal age-at-death from the pubic symphysis relies on the assessment of the biological age of the skeleton, as opposed to the chronological age of the individual. Biological age is based upon maturational developments, although a number of exogenous factors (environment, nutrition, and disease) may cause changes in the skeleton that can mask the true chronological age of the individual (Wood, Weeks, Bentley, and Weiss, 1994). As a result, the same chronological age can show different degrees of biological development (Nakamura, 1991). While there is correlation between chronological and biological age in the pubic symphysis, the specific details of the adult metamorphic process appear to vary substantially from one individual to the next. The older the individual, the more variable the potential difference between the number of chronological years lived and the actual biological condition. Certainly the measurement of age in older samples includes a higher proportion of individuals who have been affected by environmental injury or disease (Bulpitt, 1995). Thus, post-maturity symphyseal changes, observed particularly in the results of the Suchey data, are less systematic at both the individual and sample level.

The accuracy of skeletal age estimation methodology is also strongly affected by the influence of the prior reference sample distribution used in the development of age-at-death standards. Results from the present study demonstrate the potential to which particular causes of death can contribute to biased differences in age-specific mortality schedules. Comparison of the 95% highest posterior density estimates for age-at-death from both the maximum likelihood and Bayesian estimators provide further evidence of these distinctions. Thus, to improve the reliability of age-at-death estimates and avoid the bias of reference sample distributions, it is recommended that estimates of age-at-death should be based on the use of maximum likelihood estimation or the use of multiple external reference samples.

While the results of this analysis are clearly disappointing in their evaluation of the pubic symphysis data, the findings are not altogether surprising. An obvious further extension of this study is to analyze skeletal age-at-death data using a multivariate approach for obtaining the posterior densities of age conditional on observations of various skeletal indicators. While a considerable number of researchers have advocated the use of multiple morphological traits, the methods for correlation between indicators and correcting for differences among age structures of the reference samples have not been well practiced.

Although recent criticisms over the feasibility of skeletal age estimation research have been well publicized, the problems are mainly related to the need for continued refinement and testing of methods that would place age estimation studies on a firmer statistical basis. The obstacles in improving age estimation techniques and statistical methodologies are well worth confronting and extending our knowledge.

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