EXAMINATION OF AGE AT DEATH METHODS AND THE EFFECTS ON ESTIMATION ACCURACY WHEN APPLIED TO COMPUTED TOMOGRAPHY SCANS AND VIRTUAL MODELS OF MUMMIES

A Dissertation
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

James Vincent Schanandore

In Partial Fulfillment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

Major Department:
Biological Sciences

March 2015

Fargo, North Dakota

North Dakota State University
Graduate School

Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

SUPERVISORY COMMITTEE:

William J. Bleier
Chair

Summer J. Decker

Neil W. Dyer

Joy Sather-Wagstaff

Craig A. Stockwell

Approved:

03/02/2015
Date

Wendy L. Reed
Department Chair

ABSTRACT

Three-dimensional (3D) medical imaging provides a method to non-invasively examine the sub-surface structures of a mummified body, particularly the skeleton. The unique nature of both natural and anthropogenic mummification processes causes inconsistencies for estimating accurate age at death for a particular mummy or group of mummies. These inaccuracies are compounded when age at death methods are used in relation to 3D virtual models. There is a need for the examination of methods being used in mummy case studies and how they are being applied to the 3D virtual models.

My research encompassed three studies that addressed the relationship of and the variability when estimating age at death of mummies using radiological imaging. In one study, 146 published case studies were examined for which methods were used to estimate age at death. This study found that articles often provided an assessment of age, but many failed to specify the methods used to calculate the estimated age, and if specified methods were limited to certain areas of the body.

In a second study, a cohort of age at death methods was applied to a sample of 17 adult mummies and it was determined that some methods do not transpose well and consequently provided inaccurate age at death estimations when applied to 3D virtual models. Modifications to traditional osteological approaches for age estimation were sometimes necessary due to the presence of soft tissue and post-mortem changes to the body. This study proposes that more methods are needed that utilize the tools available for radiological images in order to limit the variability of transposing a traditional age at death method to virtual 3D models.

In the third study, the rim height of the auricular surface was measured using computed tomography scans of 97 living or recently deceased individuals’. These measurements targeted areas around the edge of the surface, for example the height of the apex above the surface. The rim height above the surface produced models that can accurately predict age at death.

ACKNOWLEDGEMENTS

First and foremost, this dissertation would not have been possible without the help Dr. William (Will) J. Bleier. When I did not have many options to continue my mummy research, he gave me an opportunity to do so. I will be forever grateful for that opportunity. I also thank my other committee members: Drs. Summer J. Decker, Neil W. Dyer, Joy Sather-Wagstaff, and Craig A. Stockwell. I thank Dr. James (Jim) W. Grier for editorial and statistical help. Lastly, I would like to thank Dr. Heather Gill-Frerking for introducing me to mummy research as an undergraduate student and helping me with all my mummy questions throughout my graduate career.

Computed tomography scans and other scan data were provided by the Reiss-Engelhorn Museum, the Hungarian Natural History Museum, and the Department of Radiology at the University of South Florida (USF). Dr. Decker was instrumental in the acquisition of scans and data from the USF.

I thank the Department of Biological Sciences and the College of Science and Mathematics for financial support. The department provided my salary via a graduate teaching assistantship, and the college provided research funds.

DEDICATION

I dedicate this dissertation to my family. Without the support from my wife, parents, and brothers, this dissertation would have been much more difficult to complete. Mostly, I thank my wife, Brittany, for her support, and at times prodding, for keeping me focused on my PhD program during these past seven years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LITERATURE REVIEW

Introduction

Three-dimensional (3D) medical imaging, such as computed tomography (CT), has provided a non-invasive method to examine the subsurface structures of the body, particularly the human skeleton. Due to the uniqueness of both natural and anthropogenic mummification processes, inconsistencies occur when trying to provide accurate age at death estimations for mummies. These inaccuracies are greater when one uses age at death methods of mummies with poor quality 3D virtual models. With significant increases in computing power, the use of medical imaging for research purposes on mummies is on the rise. However, few investigators have examined whether medical imaging is adequately providing the necessary detailed virtual models to make predictions about the life history and age at death of mummified individuals. Age at death estimations can be affected greatly because many of the age at death methods use qualitative features of bone, which potentially can be lost when creating a 3D virtual model. CT scanning is an innovative method; however, the question of sufficient detail to support accurate estimations regarding the life history of an individual remains unclear.

This dissertation encompasses three aspects: mummies, age at death estimation, and computed tomography (CT). The study of mummies surfaced when Napoleon discovered them in Egypt (Cockburn, 1975). For most mummy researchers, a mummy is an opportunity to learn more about a particular culture because mummies provide more data within the preserved soft tissue which is unavailable in a skeletonized individual.

In the early 1920s, observations focused on how the human skeleton changes as an individual ages (Garvin et al, 2012). These observations gave researchers the ability to identify how old an individual was without written record of age. Since the discovery of the concept that skeletal changes occur as a result of aging, researchers have been trying to find a method that encompasses all of the factors that affect the human skeleton over the life time of an individual. In other words, researchers are trying to find the most consistent method of predicting chronological age from biological age. Attempts to develop a consistent method have involved the use of both qualitative and quantitative methods in the study of the human skeleton. As a result, a researcher currently has many choices of methods to estimate age at death.

The field of mummy studies is highly interdisciplinary, and experts from different backgrounds are commonly found in the published literature. However, the mummy studies field has an anthropological background that puts into question traditional methods used when examining a mummified individual. For example, invasive procedures such as an autopsy do not respect the individual or the culture represented. As a result, radiological imaging started to play a major role. One example of these radiological imaging techniques, computed tomography (CT), was first reported by Hardwood-Nash (1977). This technology gave researchers the ability to glimpse inside the mummy without having to complete an autopsy and provided a more ethical approach to handling the dead. In addition to use of CT imaging in human mummies, it has also been applied to other research in physical anthropology, e.g., in nonhuman primates and hominid research (Tate and Cann, 1982; Conroy, 1988; Macho and Thackeray, 1992). As CT became more advanced, researchers began to create 3D virtual models of the human skeleton. In terms of analysis of mummies, 3D virtual models allowed for the potential use of traditional age at death methods to estimate age. It is now common to see mummies undergo CT scans, and the derived 3D images are used by many researchers in applying age at death methods. The question that needs to be answered is whether or not virtual models of mummies can be used to produce accurate estimates of age at death using methods that were designed for real bone.

The Mummy Phenomenon

People have been and continue to be fascinated with mummies. This fascination has even lead wealthy individuals to buy and sell mummies to create personal collections. Others acquired mummies for medicinal purposes because at one time it was thought that mummy powder, produced by grinding up mummy tissue, had curative powers. During the Egyptian craze, people from places such as Britain would hold unwrapping parties where invitees could leave with items that were inside the wrappings (Sheppard, 2012). As one can see, the value of a mummy can vary, but without doubt when there is a mummy, fascination follows. With this fascination, come misconceptions about the mummy as a person and a relic. It is a strange occurrence that when a person has died and has been preserved over hundreds of years, that the living generation treats these individuals differently than those of a person recently deceased. It would be considered strange to see an autopsy party on a recently deceased individual, but it was widely accepted to dissect an individual that had been preserved for hundreds of years. Mummies seem to have a strange effect on some people; to these people the mummy sometimes loses the human aspect and turns into an object. In order to show the human side of mummies, an examination of what a mummy "is" needs to be made.

Quite simply, a mummy is a human or animal who has somehow evaded decomposition, resulting in an individual in a preserved state. A key component in the term "mummy" is the presence of preserved non-skeletal tissue (Lynnerup, 2007). For example, skin, muscle, and soft connective tissues are commonly found preserved on human remains. How much of the mummy is decomposed versus preserved depends on conditions such as temperature, moisture, and burial location (Mann et al, 1990). In most situations, enzymes through autolysis and bacteria start to decompose the body (Vass, 2001); however, if a body is laid to rest in an environment that opposes conditions favorable to decomposition, preservation will occur without application of embalming techniques. For example, hot arid or freezing environments with dry conditions work well for preservation. Catacombs or crypts can be places to find mummies because of low moisture levels (Fornaciari, 1999). Desiccation is important, but there are always exceptions. Freezing (Hart Hansen, 1985; Hart Hansen, 1998) will halt decay, but the individual must stay in that state because when thawing starts, decomposition will resume. Peat bogs provide a unique environment where sphagnan and acidic water create an antiseptic environment that prevents bacteria from decomposing the body (Aufderheide, 2003).

Questions arise because the term "mummy" does not have specific requirements of how much soft tissue should be present or the length of preservation time (Lynnerup, 2007). For example, should an individual be considered a mummy if there is only hair present or if only a hand or foot is preserved? There are instances when there is little to no skeletal material and only soft tissue, such as those individuals found in peat bogs in Germany where the bog demineralizes the skeletal material. Since length of preservation does not have a minimum required length of time, an amusing but valid question can be asked, "Can beef jerky be considered a mummy?" Considering beef jerky as a mummy may be pushing the envelope too far because it is not a mortuary practice, but in some cultures preservation of just the skin or muscle is common (Guillen, 2004). If one has just mummified skin, it is difficult to gather accurate data in terms of age at death or stature, but factors such as diet can be determined. For some, it is difficult to consider just skin as a mummified person, but since there is soft tissue preserved, then it should be considered a mummy.

There is a wide variety of ways that an individual can become preserved, but all fall under two types of preservation: natural preservation and anthropogenic preservation (Lynnerup, 2007). Natural or spontaneous preservation involves any natural environment which prevents or limits water from continuing to aid the natural process of decomposition. As previously mentioned, preservation through heating or freezing can be seen in deserts where extreme hot temperatures desiccate the individual, or in mountains where freezing temperatures at high altitude prevent decomposition. An additional example is in Iran where large salt deposits have been known to preserve individuals (Ramaroli, 2010).

The second form of mummification is artificial or anthropogenic, i.e., mummification induced by another human. Anthropogenic mummification is most commonly found in Egypt where thousands of individuals have been mummified as part of mortuary practices (Cockburn, 1975). Another example is the Chinchorro mummies in South America, where not only the elite were mummified like in Egyptian culture, but the commoner as well. The preparation was also different than that of the Egyptians because the Chinchorro people would set aside the skin, remove all the other soft tissue, and then replace the skin using sticks and vegetation for reinforcement (Guillen, 2004; Arriaza, 1995).

Not all mummifications are obvious in terms of determining whether or not an individual was preserved through natural means or artificial means. There are examples of mummies found in Japan, where Buddhist monks of a particular mountain sect secluded themselves and ate specific foods. After the individual died, they became preserved due to the food they had eaten prior to death (Hori, 1962). In this instance, the line separating natural and artificial mummification is blurred. The monks were preserved through natural means, but made a conscious effort to preserve themselves.

The other aspect of the overall question of “what is a mummy” diverges away from the biological processes and focuses more on the human aspect of a mummy. Human skeletal remains are valuable for study, but a human mummy offers significantly more information about the individual than that of just skeletal remains because of the soft tissue preservation. For example, the skeleton can provide information on age, sex, and any pathology, such as trauma or diseases that manifest themselves by changing the structure of the bones. For soft tissues, new non-invasive technologies allow for more information to be collected; nonetheless, some method protocols use samples from the mummy, which increases the damage to the mummy. There is a fine line of minimal sampling to gain information and over sampling and risking permanent damage and lack of respect of the individual. On one side of the argument, researchers know that a mummified individual once walked, ate, and breathed, and certain methods can lead to information to illuminate aspects of past cultures, such as diet and health. On the other side of the spectrum, researchers also know that this individual once had a mother, father, or possibly children, and just because there are no known living relatives, it does not give one carte blanche access to destroy the mummy for research purposes. Researchers are now conducting studies that are less invasive in order to conserve mummies that have been taken from their original resting places, while still providing opportunities to learn more about them and their culture.

Mummies are unique relics that present an opportunity to get a glimpse into the life of an individual prior to his/her death. Just as forensic anthropologists try to determine if the death of an individual was natural or unnatural based upon the events that occurred prior to the person’s recent death, mummy researchers also try to construct the life of individuals based upon their distant past. When an individual is preserved, he/she becomes a lasting part of history like artifacts found by archaeologists. Just like archaeological artifacts, the individual will remain intact to be studied in the future, as long as there is no change to the environmental conditions surrounding the mummy. When a mummy is removed from its original environment, even an anthropogenically-preserved mummy, it is at high risk for decay through changes in humidity and temperature (Klocke, 2010), or the presence of insects and other live organisms that live off of decay. Just as artifacts need to be properly curated, so does mummified material. Today, most museums go to extra lengths to keep a mummified individual in good condition, although this has not always been the case.

Another challenge to studying mummies is the diversity of the types of mummies. When people think of mummies, most typically think of Egypt. Early in a person's education, Egypt is the place that is associated with finding mummies. If it is not in school, then it is the media or the high flying action thrillers that depict a mummy that has come back from the dead, and the backdrop is an ancient Egyptian ruin with the desert sands shown blowing in a whirlwind fashion (Wenzel, 2010). In addition to the wrapped mummies in Egypt, mummies are a phenomenon found all over the world, representing many cultures and peoples. Beginning with Egypt, one will find mummies spanning thousands of years that represent many of the great periods of Egyptian culture (Pommerening, 2010). Moving northwest to Europe, there are examples of mummies found in peat bogs (Gill-Frerking, 2010), the incorruptible saints of the Catholic Church (Wunn, 2010), and crypt mummies (Wunn, 2010; Szikossy et al, 2010). Farther west, one will find the frozen mummies of Qilakitsoq, Greenland (Fleckinger, 2010). In North America, one finds mummies in southwest United States, and in South America many mummies have been discovered in the Andean regions (Tellenbach and Tellenbach, 2010). Moving across the Pacific Ocean, one finds mummies in Oceania (Gunther, 2010; Tellenbach et al, 2010), Australia (Erckenbrecht and Klasstsch, 2010), China (Werning, 2010), and Japan (Janssen-Kim, 2010). Further west toward Egypt in Russia, there are mummies of the Scythian Pazyryk culture (Kerneck, 2010).

As one can see, the diversity of mummies is large. Each area of the world has a mummy that is unique compared to the next. The variation among mummies can cause issues when trying to collect data. This dissertation specifically examines how estimations of age at death are affected by the use of CT scans of mummies. Further discussion of age at death methods and CT scans are necessary to show why there should be a concern about age at death accuracy in relation to mummy CT scans.

Age at Death

Age at death estimation is a debated subject in the forensic and anthropological worlds. Any examination of a human body, whether it is in a forensic or a more historic setting, starts by creating an osteobiography (Franklin, 2010). An osteobiography consists of determining age at death, sex, ancestry, and stature. In modern forensics, determining these variables helps develop a general description to determine identity, if it is not known. In a more archaeological setting, an osteobiography provides more introductory demographic estimations about an individual or group of individuals; the portion of the osteobiography for this study focuses on determination of age at death.

Age at death estimation is the task of estimating the chronological age from the skeleton of an individual using qualitative and quantitative methods. Age at death estimation was not a common concept in the early 20th century, solely based on the fact that skeletal collections were not common. Most skeletal collections consisted of skeletal remains from burial sites, but no documented age at death. It was not until 1912 when Thomas Todd put together a skeletal collection with documented age at death that biological and forensic anthropologists started to gain an interest in the age-related changes of the human skeleton (Golda, 2010). The first publications showing that the skeleton changes as an individual gets older was in the early 1920s

(Garvin et al, 2012). In 1920, Todd published some of the first methods looking at qualitative features of the cranium and the pelvis.

From the early 20th century to present day, numerous methods have been developed with the main goal of estimating age at death with acceptable accuracy and precision. The first methods were qualitative, but more and more quantitative methods have been pursued to reduce observer bias. Both qualitative and quantitative methods have examined numerous areas of the body; e.g., the pelvis (Todd, 1920; Lovejoy, 1985a; Suchey and Brooks, 1990), the teeth (Paewinsky et al, 2005), and the ribs (Iscan et al, 1984a, 1984b, 1985, 1986a, 1986b; Dedouit et al, 2008; DiGangi et al, 2009).

Even though estimating age at death has been studied for many years, the variation that ultimately comes with human individuals can complicate the process in finding a truly accurate method. Researchers are pursuing methods to account for all the internal and external factors that affect the anatomy and hence the estimates.

Many factors play a role in how age manifests itself in the human skeleton. Genetics, environment, and lifestyle can affect how accurate methods are with a particular skeletal sample. Starting at birth, the human body goes through changes as it ages. For example, subadult epiphyseal union of certain bones is a common way to estimate age at death (Schaefer et al, 2009); however, factors such as genetics play a role in how rapid epiphyseal closure occurs, which additionally may be affected by nutrition and lifestyle. It is also common to use teeth as indicators of age because teeth are not as affected by nutrition as epiphyseal plates (Scheuer and Black, 2000). Many environmental factors, such as diet, may not be known when dealing with individuals that have been deceased for a number of years. Another factor that needs to be considered is whether male and female subadult individuals biologically age at different rates. It was shown in hand and wrist development that girls tend to mature faster than boys (Greulich and Pyle, 1959). When analyzing subadult mummies, how the type of preservation may have affected the appearance of growth plates or teeth, which can effect age at death estimations, needs consideration. If preservation type cannot be accounted for, the next best approach is to identify methods that work best for different types of preservations.

When an individual reaches adulthood, the ability to accurately estimate age decreases. Adulthood is defined many ways. For example, in a general biological setting, adulthood is reached when an individual attains sexual maturity or has the ability to reproduce. For humans, this could mean adulthood starts at around 10 to 12 years of age; however, for most 10- to 12-year-olds, there is much growth to be completed before reaching maximum stature. Osteologically, adulthood begins when the growth plates have fused, and third molar eruption and fusion of the spheno-occipital synchondrosis are completed (Garvin et al, 2012). When estimating age at death for an adult, there are no subsequent growth stages that clearly mark points of age development. Capturing all the factors that could affect an age at death estimation into one method is difficult.

Just as in the subadults, there are many other factors and lifestyles that can affect the appearance of bones features, making it difficult to align chronological age with biological age. An example of a misaligned estimation of age at death would be when individuals are chronologically younger but appear older biologically because their lifestyle caused more stress on their bones. Another factor to consider is the sex of the individual. Berg et al (2008) reported that the pubic symphysis ages differently in terms of qualitative appearance in females versus males. Ancestry is another complicating variable. For example, the Lovejoy 1985 method targeting the auricular surface when applied to an Asian individual will lead to an underestimation of age at death (Schmitt, 2004). Underestimation occurs because the method was developed on white individuals, and so it does not account for the variation in Asian populations. Lastly, when dealing with adult mummies, caution is advised for a particular individual based on the preservation. For example, peat bodies have bones that are demineralized and can cause important skeletal age features to appear older (Gill-Robinson, 2005).

Variation of the human skeleton often produces wide ranging statistical results. Since there is no standard statistical protocol, researchers often do not use the same statistical approaches (Ritz-Timme et al, 2000). Statistically illustrating that a method is accurate is often debated because accuracy is not standardized (Ferrante and Cameriere, 2009). For example, some methods deem predicting within 10 years of true age is accurate compared to the next method that deems being accurate within 15 years. Most methods that have been developed are more or less precise, in that after many measurements/observations by multiple observers the estimates are similar. However, when it comes to age estimation, one wants to approximate true age as much as possible. Even with a small amount of error between observers, the accuracy of the estimated age to the true age could be significantly different. Inaccuracy is more prevalent with adult individuals because it is more difficult to interpret age-related changes. On the other hand, subadults are easier to estimate actual age, because the continual change of the skeletal system is easier to interpret as adulthood is reached.

Researchers have attempted to address variation in the body by examining the types of methods and statistical procedures used to analyze data from skeletal collections. When dealing with qualitative methods, one needs to account for what each researcher is observing when estimating age. Experienced observers will have seen most age related changes for a particular feature, whereas an inexperienced observer may not have. Additionally, qualitative methods tend to be inaccurate because resulting age predictions typically mirror age demographics of the sample used to create the method (Bocquet-Appel, 1982).

As age at death estimation methods progressed, it was realized that qualitative methods are not as accurate as one would hope. Even though qualitative methods do have some inaccuracy issues, traditional methods such as Todd 1920 are still used today (Garvin and Passalacqua, 2012). However, more quantitative methods are being developed in hopes to reduce observer bias and inaccuracy, but many of these methods incorporate technology, such as radiological images, that is not always available. Thus, many biological anthropologists will fall back on the traditional methods when technology is unavailable. The development of qualitative methods will likely never disappear; instead traditional methods are being revised through the use of various statistical assumptions (Samworth and Gowland, 2006). These assumptions give rise to statistical analysis, such as transitional analysis (Boldsen et al, 2002), which attempts to remove the bias in estimating age at death for skeletons.

Another concept, which this thesis will utilize, is multifactorial analysis to create a summary age at death (Lovejoy, 1985b; Bedford et al, 1993). Aging is not always consistent uniformly across the skeletal system. For example, it is possible to find evidence of an individual appearing to be 5 to 6 years old according to the teeth, but only 2 to 3 years old in epiphyseal closure. The hypothesis behind multifactorial analysis is that more data points enhance the chance of finding the best approximate age at death; in essence, a multi-method approach across the body should be considered (Martrille et al, 2007). Using a multi-method protocol could more accurately capture the chronological age. Accuracy of a multi-method approach increases over a single-method approach (Sanders et al, 1992; Lovejoy, 1985b). The idea combines the estimations of different methods across the body to get an average of all estimates, referred to as summary age. The rationale follows the notion that (1) the particular age at death features will exhibit different age estimations based on given features, and (2) any observed inaccuracies should be minimized because other methods should help correct any mistakes made by the observer. The studies that have incorporated this multifactorial approach have produced better correlation to the chronological age (Lovejoy, 1985b; Bedford et al, 1993).

In summary, age at death is a complex subject because the human body is complex. The variability among individuals makes it difficult to accurately estimate age at death for adults and to create methods that identify this variability. Subadults typically have distinct age marks as they develop, making estimating age at death more accurate. Quantitative methods and statistics are aimed at standardizing age at death estimations, because estimating age at death can be as much of an art as it is science (Maples, 1989). This statement is troubling because age at death estimation should be based on the scientific method. Maples (1989), however, does state an important point. If a method uses qualitative features that are not easily distinguished, then observer experience will have a significant effect on accuracy. In general, there is a high variation in the aging process, and aging mummies does not escape this variation. There are few methods dedicated specifically to estimating the age of a mummy, largely due to a limited collection of mummies that have documented age at death. Also, there are few methods applied in current mummy research where 3D imaging technology was used in the analysis. In most cases, a researcher has to transpose method protocols into a virtual world, and many times this transposition may not work with the technology well enough to produce accurate estimations. If methods are not designed specifically for estimating age using 3D imaging, then which traditional methods that will effectively translate to accurate results must be identified; however, the best option is to put more time into creating methods tailored specifically for 3D imaging.

Technology and Mummy Studies

Early mummy research was initiated with Napoleon Bonaparte’s invasion of Egypt which resulted in studies of various artifacts and mummies through means of autopsy (Aufderheide, 2003). Typically, an autopsy involved the removal of all the wrapping and then performing a Y incision to investigate the chemicals used for Egyptian mummification (Cockburn, 1975). Destructive methods such as autopsy started to lose popularity because anthropology had become a field that put the culture or people being studied above the research; some anthropologists viewed performing an autopsy on an Egyptian mummy as disrespectful to the Egyptian culture. When an autopsy is performed, Egyptian culture sees the body as destroyed thus rendering it useless to the dead individual in the afterlife. Ultimately, conservation of the mummified individuals or material became important to museums conducting mummy research. Methods became less invasive, while still obtaining relatively the same information as an autopsy. Technologies such as radioisotopes, endoscopy, infrared reflectography, and radiology have contributed to the study of mummies (Lynnerup, 2007). This dissertation is mainly concerned with radiology and specifically computed tomography (CT). Godfrey Hounsfield created the first CT scanner in 1967, and in 1971 the first CT scanner was installed (Lynnerup, 2007). Now multi-slice scanners are utilized, resulting in better volume rendering (Hsieh, 2002). CT uses X-rays taken from all angles and assigns a xyz coordinate system to the images. The images can be viewed in 2D from multiple planes, and the voxels that create the 2D images are given a value on the greyscale to represent attenuation. One can then use the voxels and the xyz coordinate system to create a 3D virtual model; basic osteological methods can then be applied to determine characteristics such as age at death (White and Folkens, 2000). It was not until 1979 that CT radiography was used on a mummified individual (Hardwood-Nash, 1979). CT imaging is a technology that allows the viewing of human remains in slices and aids in medical diagnosis of diseases in a noninvasive manner. The need in biological anthropology to work with human remains within an ethical and respectful framework gave rise to the use of such new techniques. Anthropological ethics viewed a mummified individual as a deceased person, whose peace should be considered, and it should be considered unethical to violate the individual's beliefs and customs (Holm, 2001). CT gives researchers a chance to respect the individual as well as gain information that can answer questions about particular cultures. Since 1979, there has been an increase in the use of medical imaging for the study of mummies. The increase can be attributed to a couple of factors including improved medical imaging technology and availability and increased interest in the conservation of mummified individuals.

The first and foremost benefit of CT scanning is that it provides an excellent alternative to the autopsy. Many discoveries were learned through the use of autopsies; however, CT scans provided similar data without damage to human remains. CT imaging does have its limits. For example, analyses such as stable isotopes for determination of diet (Katzenberg, 2000); biochemical analyses such as blood group typing (Kyls et al, 1999); and analysis for trace elements, metals, or inorganic substances found in hair (Sandford and Kissling, 1994) cannot be accomplished. The benefit of being nondestructive overshadows many of the issues that arise with CT scanning in relation to mummies and age at death estimations.

As non-invasive as a CT scan can be, there is still potential damage to a mummy. Every time a mummy is transported for scanning purposes there is risk of damage. The other risk is radiation emitted from the scanner. Scans cause no or minimal damage, but the cumulative effects of repeated scans on the same mummy are unknown (Matisoo-Smith and Horsburgh, 2012). If a mummy is to be scanned, it should be done thoroughly the first time so subsequent scanning will be minimized. Another scanning issue it that there is no standardized protocol for how a mummy should be scanned. A protocol in this sense refers to the appropriate slice thicknesses and intervals, and kilovolts (kv) and milliamp seconds (mAs) needed to create a good image. Standard medical protocols produce images of mummified remains using thicker slices, which may be appropriate for medical diagnosis, but are not sufficient when trying to make an accurate age at death estimation.

Another issue is the relationship between age at death estimation and CT scans. Do traditional age at death methods provide accurate age at death estimation when used with the CT imaging? Studies have started to emerge which test the various concerns with CT imaging and age methods (Telmon et al, 2005; Villa et al, 2013; Dedouit et al, 2008). Validation studies like these are important to ensure that CT scanning is not just used as a neat investigative tool, but a tool that can gather accurate information to better our understanding of a mummified individual. Validation studies are valuable because they show which methods have higher accuracy when transposed to CT imaging. Thus, the scans of mummies need to follow the same scan protocols as the validation studies. If mummy scans do not mimic the protocols, e.g., in terms of slice thickness, then there might be a decrease in accuracy. The other aspect that needs to be mentioned is the fact that age at death methods used skeletal material from skeletal collections. In essence, the bones used in some of these studies are in good, high quality condition. Skeletal material of mummified individuals is often of lesser quality. A great example of this is the peat bog bodies from northern Germany. As mentioned earlier, the peat is acidic and causes degradation of the bones, thus methods need to be adjusted to provide accurate age at death data

(Gill-Frerking, 2011). The same question can be asked about Egyptian, Peruvian, or even crypt mummies. How should a particular mummy be scanned in order to get the best results? Records of all CT information should be shared, and mummy case studies should include the specifics of the scans in the methodology because that information is important to future protocol development.

Lastly, are researchers using the technology in a scientific manner. O'Brien et al (2008) examined CT imaging of mummies from 1979 to 2005 and found that only 9.7% of the papers were hypothesis driven. This statistic is alarming because if CT scanning of mummies is going to be validated, then the research needs to be based on the scientific method. This is critical for acceptance of non-invasive imaging by the scientific community. CT scanning cannot be just used as a tool for curiosity, but must be used to scientifically further our knowledge and conserve the unique relics that are mummies.

PAPER 1. IDENTIFICATION OF AGE AT DEATH METHODS IN PUBLISHED MUMMY CASE STUDIES

Abstract

The goal of this study was to identify methods that have been used in mummy case studies to estimate age at death. The study involved searching the published literature and finding 146 case studies of mummies in which age at death was estimated. The case study search was not limited to any one search engine because mummy case studies appear in many different journals as a result of its interdisciplinary nature. The case studies were examined for an estimation of age at death. If an estimation was provided, then the methods used to create that estimation were recorded. Once all the case studies were analyzed, a list was compiled of the methods used in estimating age at death in mummies. This study found that many diverse methods were used to estimate age at death. Within the 24 case studies where methods of estimating age at death were included in the publication, 54 age at death methods were cited. Among these methods were traditional methods that have been used for years and can be found in many osteological texts and field manuals.

Introduction

In most published mummy studies, there is a lack of information on what methods were used to estimate the age at death of mummified individuals. Garvin and Passalacqua (2012) developed a survey to identify the various methods being used by physical and forensic anthropologists to estimate age at death. They surveyed people thought to be mainly from the North American forensic anthropology community, and the survey was distributed to members of the American Association of Forensic Sciences. A review of the diversity of mummy case studies reveals that many journals and disciplines around the world are represented in the study of mummies. Thus, the survey completed by Garvin and Passalacqua (2012) might not be a good representation of methods used in mummy studies. It is important to identify which methods are being utilized in order to determine best practices for estimating age at death. Age at death is an important and complicated task; if less reliable methods are used, then there is a potential for less accurate estimations for age at death.

Most researchers who have any experience in studying mummies have an idea of what methods should be used to estimate age at death. However, the variability of mummified individuals may affect the choices a researcher makes when considering age at death. It is not uncommon to find mummies that limit the types of methods that can be used based on preservation and other factors. For example, conditions of the mummy's preservation could affect parts of the skeleton that are used for estimation of age at death. Also, there are mummies with only partial remains, which also limits the methods that can be used. For most mummies, preservation factors are examined and certain methods are chosen based on the fact that selected methods may provide the best estimator for age at death. Thus, methods thought to be the most accurate may not be chosen, which cannot be avoided in many cases. In 1979, a new technique, computed tomography (CT), was added to the complex of methods for aging mummies (Hardwood-Nash 1979).

Generally speaking, more mummy case studies are now using CT imaging because it has become more available, and it provides a non-invasive approach for analysis of a mummified body with little to no significant damage. In this study, many of the case studies that utilized CT scans were published from 1990 to the present. How does this affect age at death estimation? Mummy case studies that utilize CT imaging are using standard age at death methods. Since many current and past methods were developed on real bone and not virtual bone, there is a question of whether or not the virtual model is a good representation of the real bone. A second question is whether or not accuracy of methods developed using real bone is affected when transposed and applied to a virtual model. Some aspects of real bones cannot be replicated in the virtual models. For example, during aging the auricular surface has features that change (e.g., textural features), and these changes cannot be replicated in the virtual models (Lynnerup, 2007). In the past decade, some aging methods have been investigated to determine if the 3D virtual images produce the same results as the real bone methods (Telmon et al, 2005; Villa et al 2013; Dedouit et al, 2008). Three-dimensional virtual models are accurate enough to be used in virtual autopsies also known as "virtospy." Studies have shown that virtospies can be more accurate than a standard autopsy (Thali et al, 2003). It has also been shown that aspects such as stature (Giurazza et al, 2012), sex (Decker et al, 2011) and ancestry (Mehta et al, 2014) can also be elucidated. Validation studies like these are important to gather evidence to document that traditional methods can be transposed and used on a 3D virtual model. If CT imaging is going to be used, then methods that are known to transpose accurately to virtual models should be used. This study will identify whether or not validated methods are being used.

The goal of this study was to identify what methods were being used to estimate age at death for mummies. Specifically, this study addressed what common age at death methods were being used in relation to CT imaging or in a traditional non imaging setting and if the methods used in mummy case studies aligned with the most commonly used methods in physical and forensic anthropology. Method alignment between this study and the study by Garvin and Passalacqua (2012) is moderately important because methods used in forensics are presented in the courts; therefore, one would assume the most reliable methods are used. On the other hand, mummified individuals have issues that need to be considered, which could affect the methods used to estimate age at death.

Methods

In this study, a survey was not used to gather data about what methods are being used to estimate age at death for mummies. Instead, case studies in the published literature were sampled. The sample included 146 case studies pertaining to a mummy or mummies. When determining what is considered a case study, a broad definition was used. Any peer reviewed literature that used a mummy as the fulcrum of the research was included in the sample. Sample size would be substantially reduced if case studies were selected based on whether the study was specifically identified as a case study. The date of publication was also considered in the sample. Because the goal was to gather information about age at death methods being used, case studies before the 1920s were excluded because published age at death methods were not published before then (Garvin et al, 2012). Additionally, when selecting cases studies, it was important to include studies that were examining a whole body. In these cases, researchers were not limited to what age at death methods could be used. This would also eliminate any possible bias to any particular method or area of the body. For example, case studies that had only a skull obviously would be limited to age indicators of the skull; therefore, if there were a large cohort of case studies with just skulls, chosen age at death methods would be biased against methods utilizing other regions of the body.

Besides excluding case studies prior to 1920 because the lack of the published age at death methods, there was no discrimination against case studies based on the year published. However, it was realized that there could be a bias to older methods; therefore, the sample was split in half. Approximately one half of the case studies were reserved for publications prior to 2001 and the other half for 2001 to the present.

The search for case studies was not limited to any one search engine because a number of case studies could be found in small, obscure journals that are not found in some of the main stream search engines. In order to increase the overall sample size, any mummy case study that could be found was used, while adhering to the criteria noted in the previous paragraphs.

Once all the mummy case studies were collected, they needed to be categorized because not all cases studies listed a citation for the method used to estimate age. In order to organize the results, five categories were created. Category 1 consisted of mummy case studies that included age at death estimations, the areas of the body examined, and the citation of the actual method(s) used to provide evidence. Category 2 included case studies that provided age at death estimations and references to the areas of the body examined, but no citation of a method(s) used. Category 3 included case studies that provided age at death estimations and no reference to the areas of the body examined or method citation. Category 4 includes case studies that did not include age at death estimations because the age was already known based upon some type of documentation. Finally, Category 5 included case studies that did not provide age at death estimations.

Following categorization of the case studies, methods used for age estimation were recorded from those case studies. In some instances, the case studies provided reference to a textbook or osteological field manual, which did not provide enough information to know what methods were used. Because textbooks provide information on many age at death methods, the osteological texts were examined for the methods that were highlighted as more reliable and then they were recorded. Once all the age at death estimation methods were recorded, they were examined to determine frequency of use.

Results

At the end of the search, 146 mummy case studies (citations in Appendix I at the end of this chapter) were collected incorporating over 700 mummies. Fifty-five case studies were published from 1922 to 2000, and 91 case studies were published from 2001-present. Once the methods were categorized, the following results were observed. Category 5 had the highest percentage (40%), while Category 3 had the lowest percentage (8%). Rankings and percentages are presented in Figure 1.

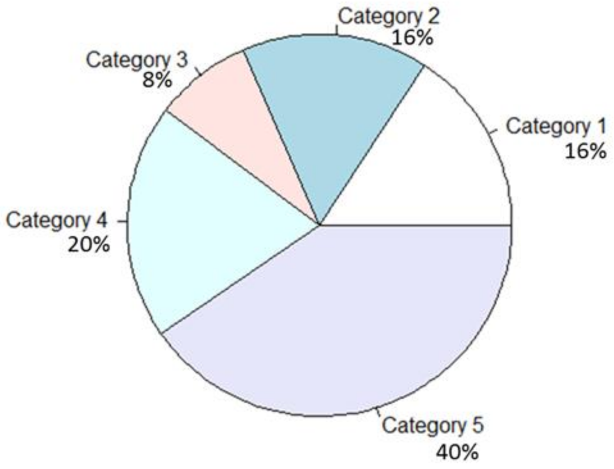

Figure 1. Age at death category breakdown. Shows the percentage of the 146 case studies in each of the 5 categories. Category 1: Percentage of case studies that provided age at death, area of body, and methodology. Category 2: Percentage of case studies that provided age at death and area of the body examined, but no methodology. Category 3: Percentage of case studies that provided just age at death. Category 4: Percentage of case studies provided an age at death that was known via historical documentation. Category 5: Percentage of case studies that provided no age at death.

Across all the case studies sampled, 54 different methods and ten different areas of the body were used to estimate age. The methods and areas of the body included (1) teeth (AlQahtani et al, 2010; Naylor et al, 1986; Grobkopf, 1990; Demirjian et al, 1973; Miles 1963; Ubelaker, 1989; Kvaal et al, 1994; Lovejoy et al, 1985b; Nolla, 1960; Engstrom et al, 1983; Nortje, 1983); (2) wrist development (Greulich and Pyle, 1959; Johnston and Jahina, 1965); (3) long bone length (Ubelaker, 1989); (4) pubic symphysis (Todd, 1920; Gilbert and McKern, 1973); (5) auricular surface (Lovejoy et al, 1985a; Gulekon et al, 2001); (6) epiphysis union (Ubelaker, 1989; Suchey et al, 1984; Iscan and Kennedy, 1989; France and Horn, 1988); (7) suture closure (Meindl and Lovejoy, 1989); (8) radiographic changes (Walker and Lovejoy, 1985); (9) histomorphic analysis (Stout and Teitelbaum, 1976); and (10) field manuals/osteological text books (Aufderheide, 2003; Angel, 1980; Bass, 1995; Ubelaker, 1999; Buikstra and Ubelaker, 1994; Ferembach et al, 1980; Scheuer and Black, 2000; Lusted, 1972; Watson and Lowery, 1962; Brothwell, 1981; White and Folkens, 2000; Williams et al, 1989). The field manuals and osteological texts had many methods as part of the text. The methods that were highlighted by the texts were recorded.

The age at death methods specific for adults included Todd 1920,1921; Todd and Lyon, 1924, 1925; Suchey and Katz, 1986; Brooks and Suchey, 1990; Mann, 1987; Meindl and Lovejoy, 1985; Nemeskeri et al, 1960; Lovejoy et al, 1985a; and Baker, 1984. For the subadults, methods included McKern and Stewart, 1957; Mann et al, 1987; Mincer, 1993; Moorrees et al, 1963a, 1963b; Ubelaker, 1978, 1989; Caffey, 1961; Francis and Werle, 1939; Girdany and Golden, 1952; Greulich and Pyle, 1959; Pyle and Hoerr, 1955; Demirjian et al, 1973; Demirjian and Goldstein, 1976; Maresh, 1955; McCarthy and Ogden, 1982; Ogden et al, 1978; Ogden et al, 1981; Ogden and Phillips, 1983; Ogden and McCarthy, 1983; and Ogden, 1984a, 1984b, 1984c.

The most popular methods for adults included Todd, 1920; Lovejoy et al, 1985a; Todd and Lyon 1924, 1925; and Brooks and Suchey, 1990. The areas of the body examined in these five cases were the pubic symphysis, auricular surface, and suture closure. For subadults, the most popular methods for age estimation were tooth development (Ubelaker, 1989; Demirjian et al, 1963; Nolla, 1960; and Moorrees et al, 1963a, 1963b) and epiphyseal plate closure and long bone length (Greulich and Pyle, 1959; Maresh, 1955; and McKern and Stewart, 1957).

A comparison was made between the results of the Garvin and Passalacqua (2012) study and this study. Comparisons could only be made for the adult methods because no studies for subadult methods that were similar to Garvin and Passalacqua (2012) were found. It also should be noted that Garvin and Passalacqua (2012) focused their survey on just 5 areas of the body for age at death estimations, whereas this study included many areas of the body.

Garvin and Passalacqua (2012) found that the pubic symphysis, sternal rib ends, and auricular surface were the top three areas of the body identified as personal preferences for forensic anthropologists when they needed to determine age at death. My study found that the pubic symphysis, auricular surface, and the sutures were the top three areas of the body examined. It was apparent that most methods were common to both studies; the only difference was a limited use of sternal rib ends within the mummy cases reported by Garvin and Passalacqua (2012).

Commonality between the two studies was also observed when the various methods were examined. The Garvin and Passalacqua (2012) survey reported that physical and forensic anthropologists preferred the Brooks-Suchey (1990) and the Todd Phase (1920) methods when examining the pubic symphysis for age at death estimations. This study found that the Todd Phase method was also the most preferred among mummy case studies, and the Brooks-Suchey method was less preferred for estimating age at death. For the auricular surface, the Garvin and Passalacqua (2012) study and my study found that the method reported by Lovejoy et al (1985) was the most preferred. Garvin and Passalacqua (2012) found that the method by Buckberry and Chamberlain (2002) was popular with physical and forensic anthropologists, but was only used in one of the mummy case studies included in my study. For the sternal rib ends, this study found that the method used by Iscan et al (1984) had limited use within mummy case studies, while the Garvin and Passalacqua (2012) survey found a high preference for it. For suture closure, the survey found the Meindl and Lovejoy (1985) method was commonly used, and for mummy case studies, my study found that the Todd (1924) and Todd (1925) methods were popular.

Discussion

Sampling mummy case studies to determine methods used for age at death estimations resulted in useful data. Of the 146 published case studies examined, only 24 (17%) of them reported methods used for estimating age at death. From those 24 case studies, 54 different methods were utilized. Fourteen of those 24 (58%) utilized a multi-method approach. It was also interesting to observe that 7% of the case studies estimated age at death without including any explanation of how researchers came to those conclusions. This can be problematic since there is a lack of evidence to support claims. O’Brien (2009) reported few studies that used CT imaging had a hypothesis driven question. With any scientific venture or hypothesis driven question, claims need to be documented with evidence, and my research revealed that in many cases supporting material for claims was not provided. Not only was it a problem for my study, but it can be a problem for anyone who may repeat age estimation on the same mummy.

A wide variety of journals published mummy case studies. For most journals, this was limited to one or two articles.   Slightly more than 20% of the case studies were found in journals where one would expect such reports, e.g., anthropological, archaeological, and paleopathological journals. About 18% of the published mummy case studies were found in radiological journals. In terms of use of technology, 47 of the total case studies utilized some type of medical imaging, and 33 of these 47 were published since 2001, indicating a significant increase in the use of medical imaging. Anatomical and forensic journals accounted for 11% of the case studies. The other 51% of the case studies were published in specialized journals, such as *The Knee.* One reason for case studies appearing in a large variety of journals, 91 journals in my study, is that few journals specifically focus on mummies. Of the 146 case studies, just 21 case studies were found in journals whose focus is mummies, which makes it quite difficult to find case studies. For future direction, it would be useful to have journals dedicated for mummy research; current examples include Yearbook of Mummy Studies (first published in 2011) and the Mummy Congress Proceedings (published every 4 years).

Comparison of the results of this study and Garvin and Passalacqua (2012) demonstrates similar findings. It is beneficial to know that researchers within the mummy studies field are using methods that are accepted by other disciplines when examining age at death. Appropriate methods are significant in this case because many forensic case studies need to use methods that are reliable enough to be used in a court of law. Based on this study, the mummy studies field encompasses methods that are also used by many individuals in the forensic community. Some methods reported in the Garvin and Passalacqua (2012) study were not reported in any of the mummy case studies. For example, the method used by Buckberry and Chamberlain (2002) was not used in any of the mummy case studies in my sample until 2002, and only one of the mummy case studies after 2002 used the Buckberry and Chamberlain (2002) method. This result was also observed in the Garvin and Passalacqua (2012) survey. Even though more recent methods have been published, many researchers still use the older methods.

Even though similar results were found between my study and Garvin and Passalacqua (2012), it must be noted that only 6 of 146 mummy case studies used the Todd (1920) phase system to estimate age at death; nonetheless, it still was the most used method because of the diversity of methods used.

There are a couple of explanations for the diversity of methods found in this study. One question that can be asked is whether or not popular methods in a forensic setting do not work in a mummy setting. In other words, popular methods may not be suitable due to the state of preservation of the mummy. For example, bog bodies create difficulties when estimating an age of a mummy based on bone surface features that were affected by the preservation processes (Gill-Robinson, 2005). The Todd (1920) phase method and the Lovejoy et al (1985) method do not work well in bog body situations. Since each mummy is unique, one could discover that certain methods would simply not work, creating a large diversity of age estimation methods across mummy case studies.

The diversity of age at death methods can also shed light on another point. My study has identified that some types of mummies do not have a defined protocol for collecting data. For example, through trial and error, it has been observed in bog bodies that certain age at death methods are not accurate because of preservation state. Diversity was also observed with the parameters of CT scanning, e.g., slice thickness and increment. With CT usage on the rise, it is reasonable that a scientifically-based protocol should be used to examine a mummy via CT imaging. For example, both Telmon (2005) Lottering et al (2014) have assured that 3D virtual models of the pubic symphysis are accurate to the real bone; however, many of the case studies that utilized computed tomography did not have the same scan parameters as Telmon (2005), thus possibly affecting the age estimation. In terms of estimating age at death, the previous example reiterates the need for the development of “best practices.”

This study suggests that there needs to be development of “best practices.” The phrase is taken from the education field where a protocol has been developed based upon evidence, which can be used by teachers to aid in instruction of their students to promote learning. As a future direction, mummy researchers should use this frame work to create a protocol that can guide investigators. The question remains, what tools are available, and, based on evidence, which of these tools will provide the most potential to maximize the knowledge that can be gained from mummies. Age at death estimation is just one aspect of an overall mummy studies protocol which can guide researchers when utilizing CT imaging and the many other techniques used to gather information from mummies. Creating a best practices protocol will provide valuable guidelines for studying different types of mummies.

PAPER 2. EVALUATION OF METHODS FOR AGE AT DEATH ESTIMATION APPLIED TO 3D VIRTUAL MODELS OF ADULT MUMMIES

Abstract

It is difficult to produce age at death methods that can account for all of the factors acting on the human skeleton, such as diet, lifestyle, height, sex, and/or ancestry. Adding to the complexity of estimating age at death, mummies present additional factors that should be considered, such as type of preservation and bone degradation. The use of medical imaging in mummy research is increasing. The 3D virtual models produced from these analyzes potentially affect the accuracy of some age at death methods. This study used a sample of 17 adult mummies of known and previously estimated ages to test the performance of a cohort of age at death methods to identify if certain methods were more accurate when used in relation to 3D virtual models of mummified individuals. Results showed that for both experienced and novice observers some age at death methods transposed from real bone to 3D models, thus resulting in better accuracy.

Introduction

Age at death estimation has two concerns when applied to mummies. First, bone condition is different for mummified skeletal material versus non mummified skeletal remains. Environmental conditions play a large role in the condition of the skeletal state of mummies (Gill-Frerking and Healy, 2011). Skeletal collections have a controlled environment allowing for the conservation of the skeletal material which provides a good resource for creating methods for age estimation. However, when the resulting age at death methods are applied to mummies, the skeletal state of mummified bone left to the elements could have an effect on the accuracy of the age estimation methods. Secondly, mummy research is increasingly using 3D virtual models, but most age at death methods were not developed with the goal of application to virtual models. Computed tomography (CT) is a useful tool for analysis of mummies, but there may be possible accuracy issues when applying age estimation methods to virtual models generated from CT scans.

Since the development of CT scans in 1979 (Hardwood and Nash, 1979), the way researchers go about gathering data from mummies has changed. Since 2000, the number of mummy cases studies that utilize CT scanning has significantly increased compared to the period from 1979 to 1999 (See Paper 2). A large component of CT imaging is the production of virtual models. One aspect that has been readily applied to virtual models is estimation of age at death.

Currently, there are only a limited number of studies that have defined a methodological approach to estimating age at death of an individual using a virtual model. Common osteological methods that were created using skeletal collections for estimating age at death have been applied to the virtual models assuming there is no confounding effect on the accuracy of the method. Accurate virtual models can be produced to yield osteological measurements for sex determination (Decker et al, 2011). Some skeletal features used to estimate age at death also have been shown to be useful (Telmon, 2005; Dedouit, 2008); however, studies like these, validating the use of CT imaging, are limited in the published literature.

A limited number of validated methods that are known to be accurate with estimation of age at death using virtual models is problematic. Since every mummy is different from all others, using the validated pubic symphysis or the 4th rib is not always feasible. It may be more efficient and effective to develop methods that strictly use CT imaging, such as those of Barrier et al (2009).

Even though research has shown virtual models can be accurate and CT imaging can provide a way to estimate age at death non-invasively, there are two problems in the application of these methods to mummy studies. First, there are no age at death estimation methods that use mummies for an age estimation study. This can be problematic because in many cases the environmental elements that mummified an individual can adversely affect the bone quality. If bone quality is affected, then it should be a safe assumption that poor bone quality can affect results of any age estimation method applied to an individual mummy. Second, the age at death methods that have been validated do not use the same scan parameters that provide the same detail. If the same scan parameters are not used for a mummy, then it can be assumed that the same detail cannot be seen, which in the end can affect the accuracy of an age at death estimation.

This study attempts to determine which types of methods provide the best accuracy when applied to virtual models of mummy skeletal material using virtual models produced from CT imaging.

Materials and Methods

This study includes data from the medical imaging of 17 adult mummies from various parts of the world including Germany, Egypt, pre-Columbian South America, and Hungary. The CT data were obtained from museums that have previously used CT imaging as an investigative tool.

The mummies used for this research are part of the long-term research programs called the Germany Mummy Project (GMP), based at the Reiss-Engelhorn Museum (REM), in Mannheim, Germany, and the Hungarian Mummy Project based out of Budapest, Hungary at the city's Natural History Museum. The German Mummy Project was established in 2004 following the discovery of 20 mummies stored in the basement of a building of the museum. The role of the GMP is three-fold: research of all types of mummies, conservation of the mummies, and dissemination of research data in both academic and public venues (Wieczorek et al, 2009). This dissertation contributes to the on-going research at the GMP, a leader in establishing a standardized system for the scientific analysis of human and animal mummies. The Hungarian Mummy Project (HMP) plays a large role in the analysis of over 200 mummies from a church crypt in Vac, Hungary. Five mummies included in this study are from the HMP and the other 12 are from the GMP.

Kniestatt and Freiherr are crypt mummies from Sommersdorf, Germany. They were laid in a family crypt during the Thirty Years War. They were not embalmed, but as a result of the dry nature of the crypt, the individuals were well preserved. Preservation of this quality for spontaneous situations is uncommon. Preservation of cartilage was seen in both of the mummies, which allowed use of techniques for examining cartilage for age at death estimation. Kniestatt is a woman whose full name is Sophie Louise von Kniestatt. According to written records, she was thought to have died of “childbed fever” due to a possible infection after the birth of her eighth child (von Crailsheim, 2010). Kniestatt’s body was found with clenched fists and feet suggesting that she was buried alive in the crypt. Kniestatt also had a severe case of scoliosis, which she lived with for some time based on the presence of extra bone growth at the apex of the lateral curvature. The second individual at Sommersdorf is a man named Baron von Holz, also known as the Freiherr. He was a relative of the Crailsheim family and was taken in during the Thirty Years War, when he died. The CT scans of the Freiherr revealed there was a sixth lumbar vertebra instead of the normal five.

Additional mummies from Oceania and Asia are included in my sample. M7 is part of the REM collection and from the oceanic region. She is in relatively good anatomical condition except that the bones of the pez are absent. There is evidence of a degenerative spinal condition on the left side of the column. Along with the spinal condition, there is evidence of bilateral dislocation of the sacroiliac joint (Tellenbach et al, 2010). M6 is a male from Asia with a fracture on the right side of the frontal bone, which poses an interesting case. For most Egyptian mummies, the ethmoid bone was destroyed when the brain tissue was removed. M6 is similar to most Egyptian mummifications because the brain tissue is removed, but interestingly the ethmoid bone was left intact. This leads to questions of how the brain was removed from the cranial cavity (Rosendahl et al, 2010a).

South American mummies are also part of my sample and are from three collections: Lippisches Landesmuseum in Detmold, Switzerland; Reiss-Engelhorn-Museum (REM); and a collection in Delemont, Switzerland. The mummies include Detmold2, M1, and M2 from the REM, and a Delemont man and woman.

Detmold 2, also known as the Gray mummy, was found in a sand hill in Arica, Chile. She was dated back to 1340 +/- 21 years ago. She has a tattoo of an oval with a central point under the left corner of her mouth and on both breasts (Meyer et al, 2010).

Another mummy from the REM is M1, a female found with two infants, one under her head (M1a) and the other in her lap (M1b). The infants were originally thought to be children of M1. Osteological investigation revealed that M1 did not have signs of childbirth. Also, radiocarbon dating revealed that the three are not from the same time period. M1 was dated to about 1095 AD, M1b was dated to 1347 AD, and M1b was dated to 1206 AD.

M2 is a woman who was found with her arms crossed and legs crossed. The legs were crossed so that the medial side of each foot was under the opposite thigh. The woman had an elongated skull more than likely due to artificial cranial deformation in the first three years of life. Her 11th thoracic vertebra was broken to the point of being unrecognizable. Perhaps this deterioration was caused by tuberculosis, and she was possibly suffering from paraplegia. Lastly, she had baby teeth clutched in her fists with an additional one next to her ribs. It is not known if these are teeth of M2's children or if they had some other significance (Rosendahl et al, 2010b).

The Delemont man and woman are two Peruvian mummies dated to 987 years and 714 years ago, respectively. The skin of the two mummies was blackened and did not match the origin of burial. It is thought the black material was added to make the mummies look older when they were discovered. The skeleton for both mummies is in relatively good condition (Begerdock et al, 2010).

There are three individuals from Egypt (designated as III 32a, III 130a, and Nes-pa-kai-schuti) who are part of a mummy collection in Basel, Switzerland. III 32a was preserved well, with an incision on the lateral side which is typical of Egyptian mummies. There is some notable pathology present within III 130a. One pathology is a fracture to the skull; the fracture has an impact point on the left side of the frontal bone, which has one radial fracture running posterior to the left parietal bone. There is also evidence of fractures in the left forearm, left thigh, and right lower leg. III 130a was thought to be female, but after further investigation it was revealed that the individual was in fact male. Original sexing was based on the absence of male genitalia, but an osteological CT examination revealed evidence that suggested the individual was male (Rosendahl et al, 2010c).

One last individual from Egypt is named Nes-pa-kai-schuti, who was thought to be a priest during his life. Nes-pa-kai-schuti is an interesting find because he was buried in two coffins. The outer, which has no lid, has drawings on the inside, while the inner coffin has a 3D head at the head end of the coffin. The inner coffin is significantly more decorated then the outer coffin (Budde, 2010).

Lastly, there are five mummies from the Vac, Hungary collection. Found in a vault beneath a church, Michael Orlovitz, Veronica Orlovitz, Beer Annamaria, Borsodi Tereezia, and Jozef Nigrovits were discovered with 200 plus other individuals. Michael showed the most significant pathology in the lower leg. His left shin was completely broken antemortem; this was based on the fracture healing. The bone was not set; as a result, healing lead to a large callus and significant shortening of the left tibia and fibula.

All of the mummies underwent a CT scans prior to this study resulting in scan data that was collected years apart. To analyze the CT data and create the virtual models, this study used additional software called Mimics®, a product of a global company, Materialise. Mimics® uses CT scans to produce 3D virtual and prototype models. The data can also be used to generate 3D surface and volumetric reconstructions. The images from the CT scan are imported into Mimics® using Digital Imaging and Communications in Medicine (DICOM) files. Once in the Mimics® program, each slice can be viewed from axial, coronal, and sagittal planes. Through the use of algorithms, the 2D images can be converted to 3D virtual models. Mimics® also allows the user to threshold and segment individual bones to view surfaces such as articulating surfaces. All individual bones pertinent to the age at death methods used in the study were three-dimensionally reconstructed and examined. Mimics® was chosen because it is used in pre- and post-surgery patient analysis, suggesting that the software produces accurate and reliable 3D virtual models (Pham et al, 2007; Schievano et al, 2007).

It is important to note that each mummy was scanned differently; these differences affect the age at death estimations and must be considered. Properties of the scan, such as slice thickness, slice increment, kv, mAs, and pixel size, can affect the overall scan and, ultimately, the 3D images produced. Slice thickness has the most effect on how the virtual model looks. Table 1 includes all the mummies and the specifications for each scan. See Appendix I for more complete information about each mummy included in the study.

Mummy Name	kv	mAs	Pixel Size (mm)	Slice Thickness (mm)	Slice Increment (mm)
Detmold 2	120	NA	0.98	1.00	1
M1	80	NA	0.98	1.00	Varied
M6	80	NA	0.98	1.00	Varied
Basel Frau	120	108	0.76	1.00	0.5
Basel Mann	140	87.5	0.88	1.50	Varied
Nes-pa-kai-shuti	120	NA	0.98	2.00	2
Freiherr	120	33	0.98	1.00	1
Kniestatt	NA	NA	1.00	1.50	Varied
Beer Annamaria	NA	NA	NA	NA	NA
Borsodi Terezia	NA	NA	NA	NA	NA
Jozef Nigrovitz	NA	NA	NA	NA	NA
Michael Orlovitz	140	28	0.90	1.50	1.5
Veronica Orlovitz	120	120	0.92	0.60	Varied
M7	80	0	0.98	1.00	Varied
Delemont Frau	120	108	0.86	0.60	0.5
Delemont Mann	120	80	0.95	1.50	1
M2	80	0	0.98	1.00	Varied

Table 1. Mummy scan parameters. Specifications for each scan of the mummies in the sample for which specifications were recorded. NA means not available.

The methods used for this study were selected using five criteria. First, some methods were included because they were identified as commonly used in the forensic and mummy fields (Passalacqua and Garvin, 2012). Secondly, since Mimics® has the ability to gather quantitative measurements, some of the methods used quantitative measurement to estimate age at death. Third, some methods were included because medical imaging was used to gather qualitative data to estimate age at death. Fourth, other methods included were those that were sex specific. Lastly, the methods in this study included as much of the human skeleton as was available to ensure collection of maximal data.

A total of 14 methods were selected utilizing 10 anatomical features: the teeth (Paewinsky et al, 2005); the pubic symphysis (Todd 1920; Brooks and Suchey 1990; Berg, 2008); the auricular surface of the os coxa (Lovejoy 1985a; Buckberry and Chamberlain 2002; Barrier et al, 2009); the first rib (Garamendi et al, 2011; DiGangi et al, 2009); the fourth rib (Dedouit et al, 2008); the sacrum (Passalacqua, 2009); the acetabulum (Rouge-Maillart, 2006; Rissech et al, 2006); and the femur, lumbar, and cervical vertebrae (Rühli et al, 2005).

Three volunteer observers applied the selected methods to the mummy virtual models. Each observer completed two rounds of estimations of all 17 mummies using each of the 14 methods, totaling 238 age estimations per round. Each round was separated by more than three weeks. All the mummy virtual models were randomized for each round and for each method. Observers were selected based on the following criteria: One observer had extensive experience in estimating age at death using virtual models. The other two observers were novices; i.e., had no experience applying age at death methods to virtual models. The study was designed this way because experts sometimes are more experienced with some methods than others, leading to accuracy bias for methods when an observer is more knowledgeable. With novice observers, each method has equal weight and comparisons can be made to identify which methods are most appropriate for both experience levels.

Based on the literature, a multiple method approach can provide better estimation of an individual's age at death (Lovejoy, 1985b; Bedford et al, 1993). Fourteen methods were included in the study, but because some methods are sex specific, there were 13 per male and 12 per female individual.

The summary age is the average of all the estimations from x number of methods. However, many methods used in this study included an age range, e.g., 30-35 or 40-55. If a range was given for a method, the mean value was used for the point estimation for that individual. For example, if the age range were 30-40, then the value included in the summary age provided by that particular method was 35. Many times a feature will contain bone qualities that fit into two different ranges. Multiple ranges can be put together to get a single value for age at death, thus the ranges were combined and the mean value of the combined range was recorded. Other methods that do not use ranges are quantitative, and the value provided by the formulas in those methods was the value used in the summary age. Once a mummy had point estimates from all methods, the average of the point estimations (summary age) was calculated and used for comparison with the chronological age based on documentation of age at death. Often documentation of age at death was not known, and for these instances previously estimated ages were used.

Inaccuracy of each method was calculated based on how close the age at death estimation made by each method was to the actual recorded age of the individual or previously estimated ages if age was unknown. Individuals that did not have documented age at death were included in the sample because the sample size would have been reduced to 7. Even though true age is not known, it is still beneficial to collect data on whether or not observers could agree with age at death for these mummies. The mean inaccuracy of a method was measured by calculating the sum of the absolute value of the estimated age minus the true age of each mummy divided by sample size minus one (Lovejoy, 1985b).

$$Inaccuracy = \frac{\sum(|estimated\ age - true\ age|)}{N-1}$$

The mean bias was also estimated to identify which methods under or overestimated age, where the sum of the estimated age minus the true age was divided by the sample size minus one (Lovejoy, 1985b).

$$Bias = \frac{\sum(estimated\ age - true\ age)}{N-1}$$

Comparison of accuracy and bias was made among the three observers. Calculating inaccuracy and bias helps determine which methods are the least inaccurate across the sample of mummies.

To further assess which methods were most accurate, a permutation of all possible combinations of methods was examined to identify if any method or methods were commonly found in combinations that produced summary ages that significantly correlated with recorded age at death. Each adult mummy had a potential of 14 point estimations; this equates to 16,383 possible combinations of methods. Since some methods were specific to gender and some individuals do not have complete skeletons, the total combinations used in the study were reduced to 10,227. The combinations were grouped according to how many methods were used to produce the summary age. For example, combinations that included just two methods were in the Combination Group 2 (CG2). From each of those combinations, an r value and p-value for the correlation was calculated. The sample size varied depending on the methods used for the summary age. If a male method was included, the sample size was 7; if a female method was used, the sample size was 10. If a gender specific method was not used, then the sample size was 17.

All of the results were sorted by a filter created in Excel. The filter arranged the combinations in each CG such that the combinations with a high r value, a significant p-value, and a low standard error would be sorted to the top for each CG. Once the combinations were sorted, each method was counted to identify how many times a particular method was found in the list of significant combinations for each CG. Comparison could then be made to identify methods that made up a high percentage of significant combinations for each observer.

To draw further details about each method, analysis for agreement between observers within each method was also completed. Intra- and inter-observer error for each method was assessed by using the Cohen's kappa coefficient (Ferrante and Cameriere, 2009) for methods that used qualitative means for estimating age at death and the concordance correlation coefficient (Ferrante and Cameriere, 2009) for methods that used quantitative measurements.

Results

Inaccuracy and bias results revealed certain methods clearly appeared to work better with the virtual models than others (Table 2). It is important to note that of the top three methods, the first and third in Table 2 are quantitative means to determine an age at death estimation.

Method	Avg Inaccuracy	Avg Bias
Paewinsky et al 2005	5.41	-1.02
Rissech et al 2005	7.10	-1.10
Ruhli et al 2005	7.75	-1.96
Lovejoy 1985	8.38	-2.76
Garamendi et al 2011	8.90	-3.63
Barrier 2009	9.33	-1.10
Buckberry 2002	9.50	-2.25
Digangi et al 2009	9.88	-5.22
Suchy/Brooks 1990	10.41	-7.23
Berg 2008	10.67	-3.20
Todd 1920	11.19	-7.47
Rouge-Maillart 2006	11.55	-3.25
Passalacqua 2009	11.98	-8.34
Dedouit et al 2008	13.56	-5.43

Table 2. Average inaccuracy and bias. Methods used in the study from best to worst in terms of inaccuracy along with each method associated average inaccuracy and bias compiled from all observers.

Qualitative methods that are often used by researchers, such as Todd 1920, were not as accurate between the three observers as one would expect. Methods such as Barrier et al 2009 that used CT scans for qualitative observations still were not as accurate as those methods that used quantitative measurements. Regarding bias, all methods underestimated chronological age at death.

Many of the rankings changed when the number of times a method was part of a combination of methods that produced a significant correlation with a low standard error (Table 3). Results showed that Paewinsky et al 2005 remained the best method in that it appeared in the most combinations that produced a significant correlation and low standard error. More traditional methods, such as Todd 1920 or Lovejoy 1985, moved up in the ranking when they were included in a summary age.

Method	% Across all Combinations	Average % Across CGs
Paewinsky et al 2005	67	64
Lovejoy 1985	51	51
Todd 1920	48	49
Garamendi et al 2011	47	46
Passalacqua 2009	46	46
Barrier 2009	46	46
Buckberry 2002	45	46
Dedouit et al 2008	44	44
Suchy/Brooks 1990	43	44
Digangi et al 2009	43	43
Rouge-Maillart 2006	41	41
Ruhli et al 2005	35	35
Rissech et al 2005	33	36
Berg 2008	14	13

Table 3. Method performance in summary ages. The second column (% Across all Combinations) is the percentage a method was found in all combinations of methods that produced a summary age with a significant correlation with mummy age at death. The third column (Average % across CGs) lists the average percentage a method was found per combination group that produced a summary age with a significant correlation with age at death.

With the novice observers, it was also observed that increasing the number of methods increased the percentage of significant methods per CG, which suggests that increasing the number of methods included in a summary age can increase accuracy for novice observers (Table 4).

Combination Group	Novice 1	Novice 2	Sample Size
CG1	11	21	28
CG2	22	28	180
CG3	12	10	678
CG4	37	41	1760
CG5	43	47	3212
CG6	47	51	4356
CG7	51	56	4356
CG8	53	60	3234
CG9	54	63	1760
CG10	56	63	682
CG11	53	63	178
CG12	54	68	28
CG13	50	100	2

Table 4. Percent of significant correlations between summary age and age at death per combination group. Percentage of combinations that had a significant correlation to age at death of the mummy sample per combination group. As the number of methods increased, the correlation to age at death increased for the novice observers.

This study used the Cohen’s kappa coefficient to analyze the agreement between observers for methods that used qualitative means to provide an age at death. The following scale was used to interpret the kappa values, which range between 0 and 1, with 1 representing perfect agreement:

$K < 0.4$: poor agreement,

$K \geq 0.4$ and $k < 0.6$: moderate agreement,

$K \geq 0.6$ and < 0.8: good agreement, and

$K \geq 0.8$ and < 1.0: very good agreement.

For individual methods, agreement within and between observers was poor. The average kappa value for all methods was less than 0.4. All methods that used a qualitative system had poor agreement between and within observers. For each method, observers agreed between young

(<30 years) and old (>50 years) at death; thus observers did not agree when individuals were between 30 years and 50 years at death. For the two methods that used quantitative means to estimate age at death, the average Concordance Correlation Coefficient (CCC) was 0.62, with 0 being no agreement and 1 being perfect agreement.

Comparison of the final summary ages from all methods combined showed that the observers were in agreement (Table 5).

Intra Observational		Inter Observational		
Observer	P Value Round 1 and 2	Observers	P Value Round 1	P Value Round 2
1	0.37	1 and 2	0.10	0.47
2	0.12	1 and 3	0.08	0.41
3	0.06	2 and 3	0.43	0.40

Table 5. Comparison of summary age among observers. Intra- and inter-observational comparison for the summary ages produced using all age at death methods for all mummies. The high p-values indicate there was no significant difference between summary ages.

Discussion

The results in this study clearly demonstrate how different factors variously affect the accuracy of age at death methods. Two factors, scan parameters and transposing methods to virtual models, were more detrimental to accuracy than other factors such as preservation.

Even though studies such as Telmon et al (2005) and Villa et al (2013) provided results suggesting that virtual models exhibit the same features as real bone, data from my study suggest otherwise; there was poor agreement among observers for qualitative age at death methods. In light of these data, results from Telmon et al (2005) or Villa et al (2013) should not be discredited, because the scan parameters used for most mummies in my study equated to less detail in the virtual models because of poor scan parameters. Examination of the Telmon et al (2005) and Villa et al (2013) studies revealed that the slice thickness was around 0.6 mm with increments of 0.6 mm. Most of the mummy scans in my study had scan parameters of 1 mm or greater for slice thickness. In one case, the slice thickness was about 5 mm with a 5 mm slice increment. Scans with large slice thickness were not excluded from the study because the number of mummies that could be included in the study was limited and removing a mummy would reduce an already small sample size. Additionally, including mummies with large slice thickness provided evidence for why smaller slice thickness is important. For example, the mummy with a slice thickness and increment of 5 mm had the lowest agreement among observers. For the mummy scans that used similar scan parameters as those of Telmon et al (2005), the pubic symphysis had a much higher agreement between and within observers. The change from 0.6 mm to 5 mm drastically changes the detail of the virtual model (Figures 2 and 3). It is clearly evident that if one used the Todd 1920 method, the ability to make a more accurate estimate of age based on the pubic symphysis is greatly increased with 0.6-mm sections and increments vs 3-mm ones. Future mummy studies should follow scan protocols set in studies such as Telmon et al (2005) or Villa et al (2013) to capture the detail needed to estimate age at death accurately.

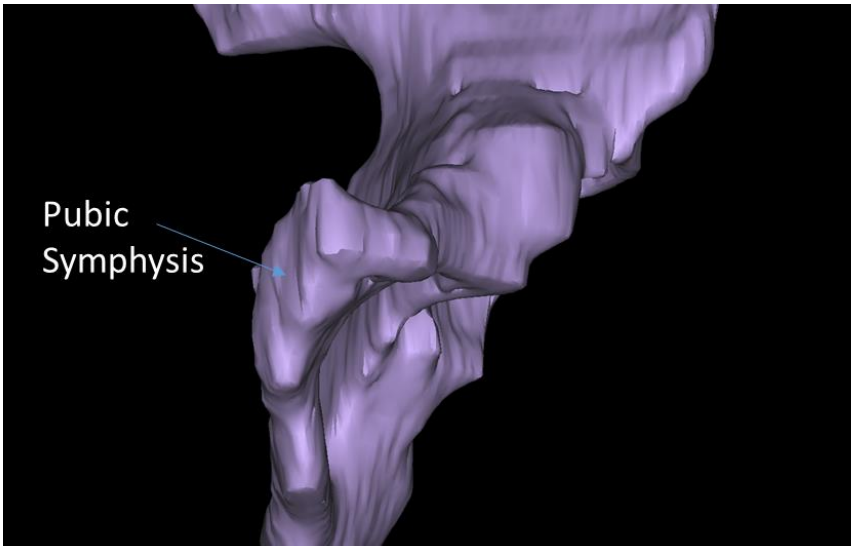

Figure 2. Virtual model of 3 mm scan. Picture of a virtual model that used a slice thickness and increment of 3mm.

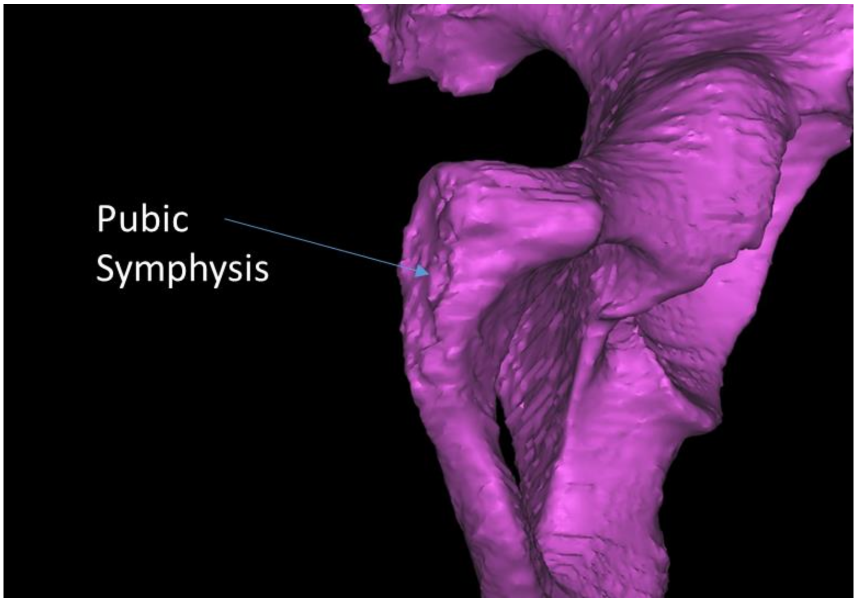

Figure 3. Virtual model of 0.6 mm scan. Picture of the same region for the same individual as in Figure 1, but using 0.6mm slice thickness and increment.

X-ray images generated from thinner slices do not adequately address all issues. Certain methods use qualitative features, such as microporosity, which are difficult to identify even with a slice thickness of 0.6 mm. For example, observers found it difficult to rate the number of micropores, which increased the discrepancies between observers and their estimations of age at death.

One aspect of real bone that is difficult to reproduce in virtual models is fine texture. Often with real bone the texture of some bone features can give insight and help estimate an individual’s age at death. Some methods included in this study used such indicators. Observers had limited ability of estimating the texture of the bone, which again increased the discrepancy between observers.

The only agreement between and within observers for individual methods were those methods that used quantitative measurements as indication of age at death. The average CCC was 0.62 across the all measurements for the two methods that utilized measurements. The low parameter had a CCC of 0.31 and the high was 0.99. There was variability in the CCC because the methods were not specifically meant for CT imaging. Even for measurements, some transposition was needed to fit the CT imaging, which lead to some discrepancies between observers; nonetheless, the Paewinsky et al 2005 method remained the most useful indicator of age at death for both individual methods, as well as when it was included in a summary age.

Lastly, results showed that summary age was an important factor in this study. This study used 14 methods. Twelve of those methods used some type of qualitative features, which resulted in poor agreement when examining each method alone. Even though observers did not agree on an age for a single method, the summary age corrects for this error and brings all observers to a common age in the end, perhaps as a consequence of the central limit theorem.

Whether qualitative or quantitative methods are used, transposing methods to a virtual model is cumbersome and leads to inaccuracy, which is problematic when attempting to produce accurate life histories of mummies. If application of CT imaging for determining age at death estimations is going to continue, the mummy studies field would benefit from producing methods that better fit the use of CT imaging. Development of methods that specifically target the use of CT three-dimensional imaging is one way to better use CT technology in relation to mummified remains.

PAPER 3. ESTIMATION OF AGE AT DEATH OF THE HUMAN SKELETON: USE OF COMPUTED TOMOGRAPHY SCANS TO MEASURE RIM HEIGHT OF THE AURICULAR SURFACE

Abstract

Research on mummies is increasingly becoming more reliant on medical imaging and the analysis of virtual models. One aspect of the analysis of mummies is estimating age at death. When estimating age at death of mummies, many of the methods that are used to estimate age at death were produced using real bone, and it is necessary for these same methods to be transposed to estimate age from a virtual model. The transposition of methods to a virtual model is not always easy or accurate. The approach in this study was to use the tools available in a post CT processing software to create a quantitative method to estimate chronological age from virtual models. A sample of 97 pelvis scans was used to take measurements of the auricular surface. The resulting data produced a model that significantly predicted chorological age of a modern and a mummy sample. Novel methods that use virtual models as the focal point are useful for the mummy studies field because of the increase use of medical imaging.

Introduction

The auricular surface is an area of the human skeleton known and trusted by many as an indicator of age. Popular methods such as Lovejoy et al 1985 and Buckberry and Chamberlain 2002 utilize qualitative features to estimate age at death (Garvin et al, 2012). Since Lovejoy et al (1985) introduced the hypothesis of using the auricular surface, more research has resulted in modifications to make the method more accurate (Osborne et al, 2004). Other studies have found the auricular surface can be applied to female and male black and white individuals

(Mulhern and Jones, 2004) with a potential to be applied to a Japanese populations (Igarashi et al, 2005).

The methods which utilize the auricular surface to estimate age at death use a qualitative approach. The surface is examined for presence or the quality of features and the change of those features over time. The features are either given a score or applied to a phase system, which in turn provides an estimation of age at death in the form of a scoring table (Buckberry and Chamberlain, 2002) or age ranges (Lovejoy et al, 1985). There have been few attempts to use just purely quantitative means to estimate age at death from the auricular surface; one example is To (2008), who examined surface area of the auricular surface in relation to age at death. Studies like Buckberry and Chamberlain (2002) attempt to quantify qualitative observations and have had some success, but the method is still dependent on observer experience to discern qualitative variables.

In a traditional biological anthropological setting, the use of methods that quantify qualitative features is beneficial to estimating age at death. In mummy studies, traditional examination of the actual bone is becoming obsolete for the most part. Since 2000, there has been an increase in the use of medical imaging technology to investigate mummies (See Paper 2). In particular, computed tomography (CT) scans have been used to examine newly discovered mummies, as well as mummies that for many years have been part of museum collections. One aspect of the mummy that is investigated through the use of CT is age at death.

Software allows researchers to create 3D virtual models of skeletal material to help estimate age at death. Applying current age at death methods to virtual models is not easy because transposing a traditional method created using real bone is not a strait forward process (See Paper 2). Thus, traditional methods would have to be tested when used in relation to observing virtual models. The results showed that qualitative methods using the pubic symphysis and sternal end of the 4^{th} rib can be transposed onto a virtual model and still provide similar results compared to real bone analysis (Telmon et al, 2005; Villa et al, 2013; Dedouit et al, 2008).

An analysis similar to the pubic symphysis and sternal end of the 4^{th} rib has not been completed for the auricular surface. One inherent problem with examining the auricular surface on a virtual model is in the fine detail. For example, Buckberry and Chamberlain (2002) used the presence and quantity of micropores. Most current mummy scans use scan parameters that do not allow a virtual model to capture microporosity. This is problematic because if one wants to apply the Buckberry and Chamberlain method to a virtual model, the microporosity portion of the method cannot be included. If one wants to use the scoring system the method provides, one needs to speculate what the score would be based on the other observable factors. This is just one example illustrating why it is difficult and sometimes impossible to transpose a traditional method to fit a virtual model.

If CT scanning is going to be a primary tool for examining mummies, then an effort should be made to develop methods that use the quantitative tools available in the imaging software to analyze the CT scan data. If quantitative methods cannot be developed, then an attempt needs to be made to translate what features can and cannot be modeled from the real bone and how to identify those features on a virtual model. This will help with the transposition of traditional methods from real bone to virtual models. The goal of this study is to quantify aspects of auricular surface and compare these measurements to chronological age.

The auricular surface is an ear-shaped pelvic area that articulates with the middle portions of the auricular surface of the sacrum (Figure 4). The auricular surface has a superior demifacet and an inferior demifacet that form the ear shape of the surface. The retroauricular area is located just posterior to the auricular surface and ends at the posterior portion of the iliac crest. On the anterior inferior edge of the auricular surface, there is the preauricular sulcus and moving a slightly more anterior lies the greater sciatic notch. The surface (superior and inferior demifacets) tends to be the focus of methods estimating age at death (e.g., Lovejoy et al, 1985). There also has been some emphasis on the apex (meeting of the auricular surface edge and the arcuate line) of the auricular joint on the ilium portion of the os coxa (Buckberry and Chamberlain, 2002).

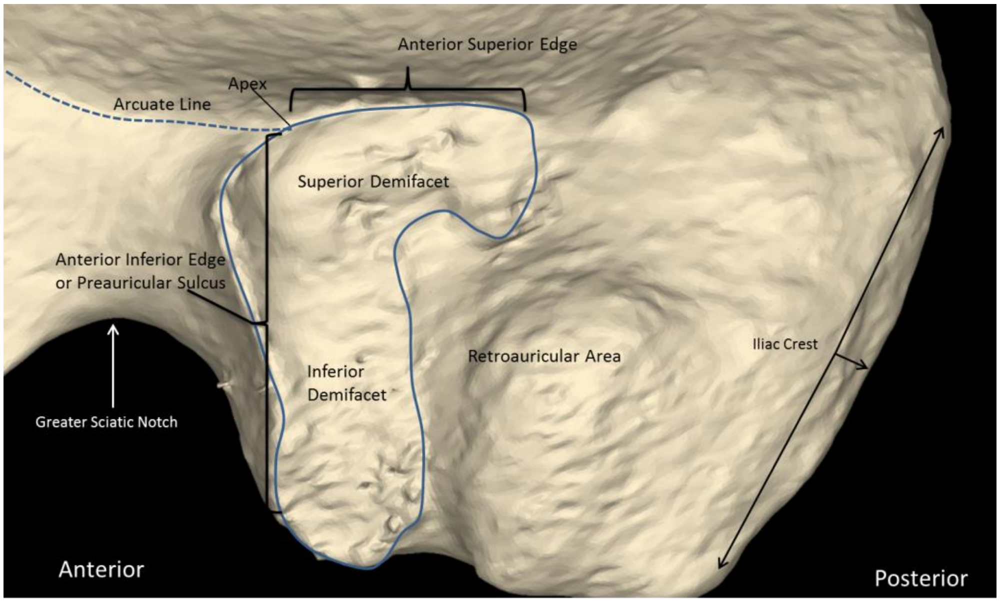

Figure 4. Auricular surface anatomy. Basic anatomy of the auricular surface. Photograph from a virtual model produced by Mimics®.

My study investigated the feasibility of using the rim of the anterior, superior and inferior edges of the auricular surface. This study hypothesize that rim height above the surface of the demifacets decreases as an individual chronologically ages, specifically, that the anterior rim shows a significant decrease in height progressing from young individuals to older adults. The difficulty is attempting to quantify the change in height of the rim on the anterior superior and inferior edges; however, the auricular surface can be measured and quantified via the use of medical imaging software.

Materials and Methods

This study used a sample of pelvis scans of both cadaver and live individuals from the Department of Radiology at the University of South Florida Morsani College of Medicine. A total of 97 pelvis scans were used for the study: 57 from cadavers and 40 from live individuals. The age range of the sample was 19-96 years. The 57 cadaver scans made up the higher end of the age range (53-96 years); scans of the live individuals ranged from 19-59 years. Ages for the entire sample averaged 62.6, with a median of 63. The slice thickness for the scans ranged from 3 mm to less than 1 mm. The sample of 97 scans was split into two groups: 66 were used to develop the model and the other 31 were used to test the model. The sample used for model development had an average age of 64.5, median of 68.5, minimum of 19, and a maximum of 96 years. The sample of 31 for testing the model(s) had an average age of 58.6, a median of 57.0, a minimum of 22, and a maximum of 96 years.

To analyze the CT data and create the virtual models, this study used additional software called Mimics®, a product of a global company, Materialise. Mimics® uses CT scans to produce 3D virtual and prototype models. The data can also be used to generate 3D surface and volumetric reconstructions. The images from the CT scan are imported into Mimics® using Digital Imaging and Communications in Medicine (DICOM) files. Once in the Mimics® program, each slice can be viewed from axial, coronal, and sagittal planes. Through the use of algorithms, the 2D images can be converted to 3D virtual models. Mimics® also allows the user to threshold and segment individual bones to view surfaces such as the auricular surface. All individual os coxa bones were three-dimensionally reconstructed and examined. Mimics® also provided the coordinate system on the auricular surface to help make the necessary calculations using xyz coordinate points. Mimics® was chosen because it is used in pre- and post-surgery patient analysis, suggesting that the software produces accurate and reliable 3D virtual models (Pham et al, 2007; Schievano et al, 2007).

To calculate the height of the rim above the auricular surface, a plane was calculated that was situated approximately parallel to the auricular surface using the rim as anchor points for the plane. In order to calculate the plane, three points are needed to form two vectors. The formulas for those two vectors can then be used to create the formula of the plane. The following formulas were used to calculate the two vectors:

$$Vector\ AB = (X_B - X_A)i + (Y_B - Y_A)j + (Z_B - Z_A)k, \text{ and}$$

$$Vector\ AC = (X_C - X_A)i + (Y_C - Y_A)j + (Z_C - Z_A)k.$$

A, B, and C are the vector points in 3D space and X, Y, and Z are the associated coordinate points found on the rim of the auricular surface. The result will be two vectors AB and AC where i, j, and k represent the three directions of each vector.

The final step is calculating the normal vector with the following formula:

$$Vector\ AB\ x\ Vector\ AC = \begin{bmatrix} i & j & k \\ Xi_{AB} & Xj_{AB} & Xk_{AB} \\ Xi_{AC} & Xj_{AC} & Xk_{AC} \end{bmatrix}.$$

The end result of the cross product of the matrix is the equation of a plane which is as follows:

$$ax + by + cz + d = 0.$$

Once the plane equation was calculated, 10 points along the edges of the auricular surface were selected. Each point has xyz coordinates from which a perpendicular distance to the plane can be calculated to approximate the height of the rim above or below a particular point. The perpendicular distance can be calculated using the following formula:

$$D = \frac{ax_0 + by_0 + cz_0 + d}{\sqrt{a^2 + b^2 + c^2}},$$

where, x_0, y_0, and z_0 are the coordinates for each individual point on the surface of the auricular joint, and a, b, c, and d represent the values from the plane equation. The distances from the plane can be used to get a sense of the topography of the surface and potentially obtain an idea of how the surface changes during the aging process.

Bone density is good indicator of age at death in dry skeletonized bone (Curate et al, 2013); however, this study used living or dead flesh bone which raised concerns. Preliminary data showed that bone density for the sample used in this study correlated with chronological age not taking in account other variables such as gender, ethnicity, etc. Based on this evidence, this study measured bone density using an algorithm that averages the grey scale of the voxels in a 50-mm^2 area in the trabecular bone just deep to the apex of the auricular surface were used to get an average density. The density was used to add a correction factor to all the measurements from the auricular surface. There were rim height differences across the entire sample, but the differences were small and the resulting models could not capture the differences. The correction factor was added in order to magnify the differences in measurements as an individual chronologically ages. A correction factor of 5 mm (CF5) was used because model improvement hit an asymptote at CF5. The correction factor was added to measurements based on range of density for the sample. For example, if density ranged from 900-1499 based on the averages measured in Mimics ®, the correction factor was scaled by factors of 5 mm. A correction factor of -5 mm was added to measurements when density was 900-999; 0 mm, for 1000-1099; 5 mm, for 1100-1199; 10 mm, for 1200-1299; 15 mm, for 1300-1399; and 20 mm, for 1400 and higher.

Two observers selected points for the plane and the 10 points on the auricular surface. A Concordance Correlation Coefficient (CCC) was used to determine agreement between observers (Ferrante and Cameriere, 2009). The CCC was calculated using the following formula:

$$p_c = \frac{2\sigma_{12}}{\sigma_1^2 + \sigma_2^2 + (\mu_1 - \mu_2)^2},$$

where, σ_{12} is the covariance between observers, σ_1 and σ_2 equals the individual variance of each observer, and μ_1 and μ_2 are the averages of measurements for each individual observer.

In an attempt to improve consistency between observers, the following protocol was used. When selecting points to calculate the rim plane, three landmarks were used. The first was the apex which has been defined in previous literature (Buckberry and Chamberlain, 2002) (Figures 5, 6, and 7). The other two points were on the superior and inferior edges of the rim (Figures 5, 6, and 7). Moving posterior from the apex on the superior edge of the surface, a point was selected just before the edge of the surface turns inferior to form the posterior edge of the superior demifacet. This point was labeled the superior edge (Figures 5, 6, and 7). The last point needed for the plane was called inferior edge (Figures 5, 6, and 7). This point was found on the anterior edge moving inferiorly from the apex. The point selected was the last point just before the edge turns posterior to form the inferior edge of the inferior demifacet.

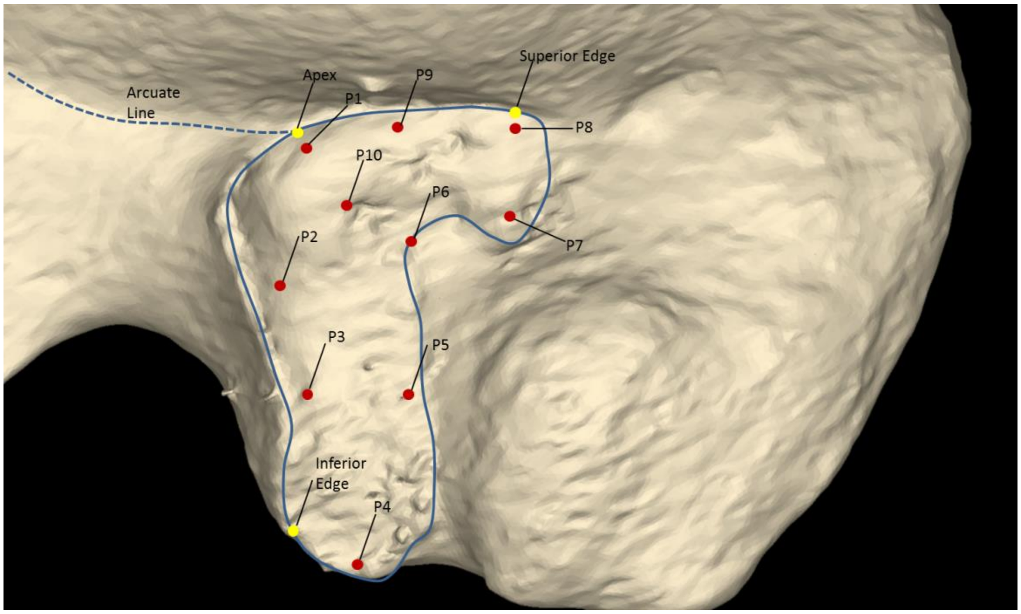

Figure 5. Critical points on auricular surface. Lateral view of the critical points used to calculate height of the rim from the auricular surface. The yellow points were used to establish the plane, and the red points are where heights from the surface to the plane were measured.

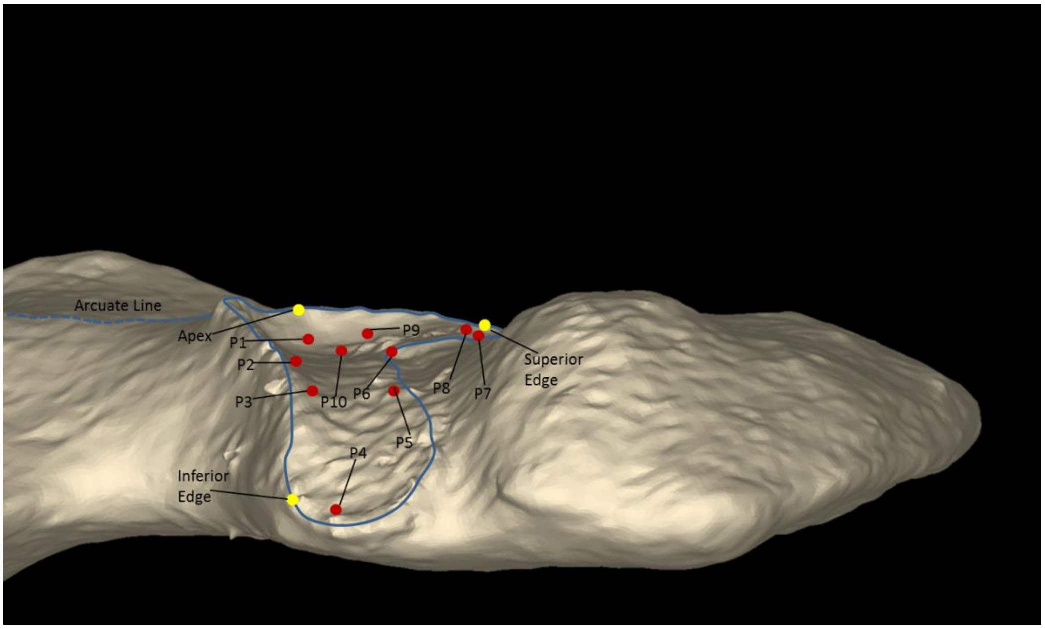

Figure 6. Critical points on auricular surface. Inferior view of the critical points used to calculate height of the rim the auricular surface.

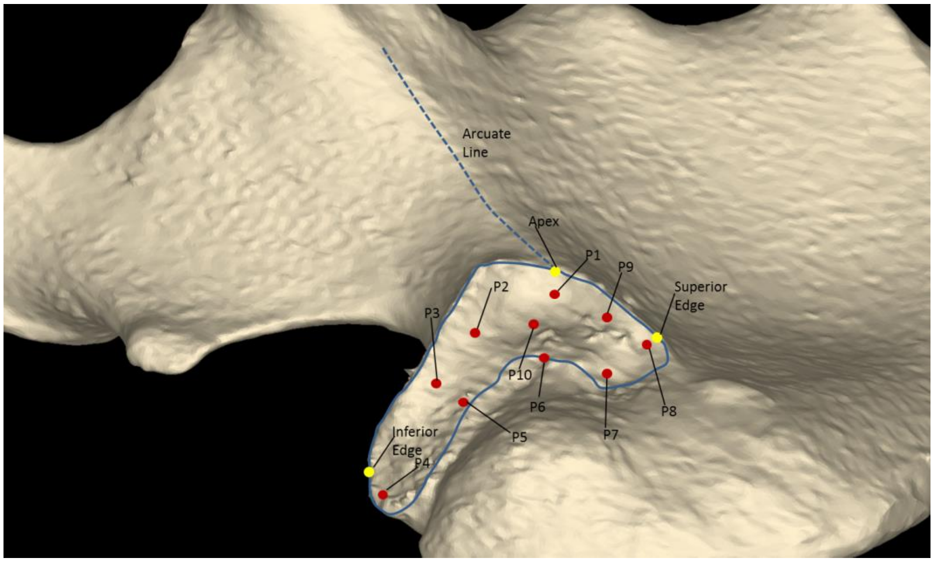

Figure 7. Critical points on auricular surface. Oblique view of the critical points used to calculate height of the rim.

Ten points were selected from the auricular surface to the plane to calculate heights of the rim. Points 1, 2, 3, 8, and 9 were found along the anterior inferior and superior edges (Figures 5, 6, and 7). These edges were hypothesized to have the most change over chronological age. These five points were difficult to locate consistently between observers because there was no clear defined border between the end of the rim and the start of the surface; the surface and the rim do not meet sharply, such as a wall and a floor. Instead there is a gradual curve called a pie curve. The pie curve represents the apex of the curve between the rim and surface of the auricular joint on the os coxa (Figure 8). For points 1, 2, 3, 8, and 9, the pie curve was selected. Point 1 (P1) was placed on the pie curve deep to the apex. P2 was placed on the pie curve approximately half way between P1 and P3. P3 was placed approximately on the dividing line between the superior and inferior demifacets. Often P3 coincided with the point at which the surface changes angle (Figure 2). P8 and P9 were positioned on the anterior superior edge; P8 was positioned on the pie curve deep to the superior edge and P9 was positioned on the pie curve half way between P8 and P1 (Figures 5, 6, and 7).

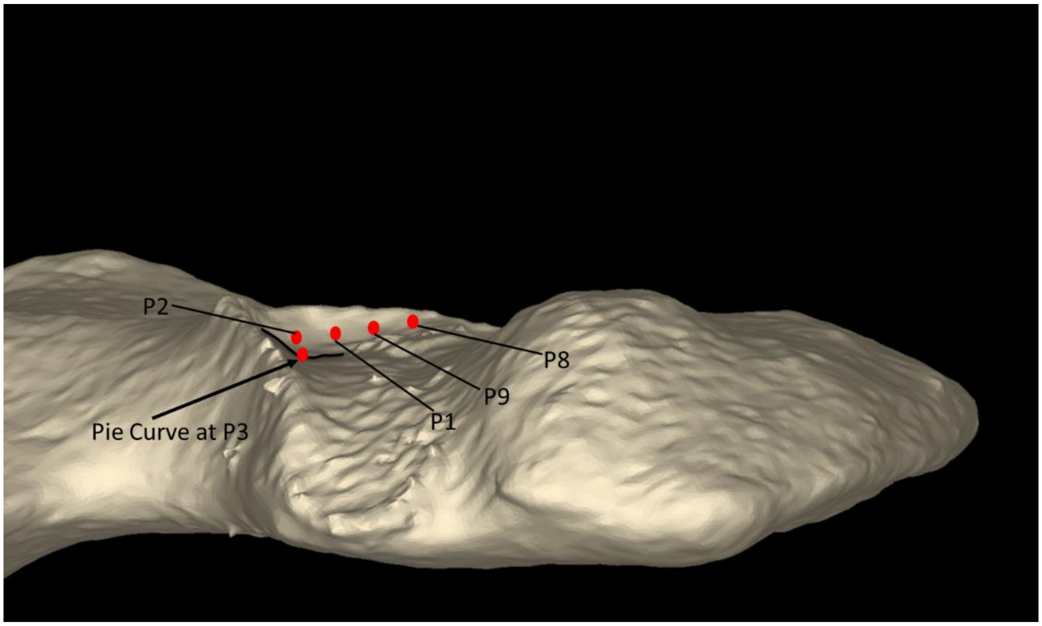

Figure 8. *Example of pie curve. An example of a pie curve where points 1, 2, 3, 8, and 9 were positioned.*

Points 4, 5, 6, 7, and 10 were positioned on the auricular surface not associated with the pie curve. P4 was placed on the inferior portion of the inferior demifacet. P5 was positioned directly across from P3 on the opposite edge. P6 was positioned on the apex of the interior curve of the auricular surface, and P7 was aligned with P8 on the opposite side of the superior demifacet. P10 was the only point not located near an edge, and it was positioned in the approximate center of the superior demifacet (Figures 5, 6, and 7).

Because 11 variables were measured, multiple linear regression was used to create a model for the sample of 66 scans. Models were created for both observers to ensure that results could be reproduced. Multiple models were produced taking into account male vs female and right vs left auricular surfaces. As a result, 9 demographic categories of models were produced. Once a model was created, it was tested using the sample of 31 scans of modern individuals and 17 adult mummies. Measurements for the test sample were acquired using just one observer, and models created by both observers were tested.

Results

When creating the model through multiple regression, not all the points were used because they were not reproducible. Points 4, 7, 8, 9, and 10 had a CCC of ≤0.60, where 0 is no agreement and 1 is perfect agreement. When those points were removed, the remaining five points had a CCC of 0.89 (Table 6), a relatively good CCC when dealing with the variability present in each auricular surface.

Point(s)	CCC
1	0.73
2	0.71
3	0.92
4	0.58
5	0.90
6	0.84
7	0.51
8	0.00
9	0.25
10	0.57
Points 1, 2, 3, 5, and 6	0.89
All Points	0.01

Table 6. Concordance correlation coefficients for the 10 points selected by both observers.

Based on the CCC results, points 1, 2, 3, 5, and 6 were used in a multiple regression analysis. Results of the multiple regression showed that measurements that target rim height above surface features can be modeled to provide plausible estimations of age at death. Models produced using each single point before the density correction factor was added did not perform well with the test sample. All models were not significant based on a 95% confidence interval. All single point models produced age estimations that were significantly different ($p<0.05$) than the test sample except for P1. When all points were used in a multiple regression analysis, models performed better with certain combinations of points; however, P1 was the best determining variable for all models.

When a correction factor was added based on density, all models improved. The model development sample had density as low as 980 and as high as 1445. New models were produced using multiple regression for all combinations of the 5 points with and without density while including the correction factor. Demographic groups were created to identify whether rim height performed better for males or males and left or right sides. This equated to 9 different demographic groups. Table 7 shows the best models for the demographic permutations of male/female and right/left.

DG	Model	Adj. r^2	F statistic	p-value	df
CF5RLMF	age= (-1.97674*p1)+(1.03023*p2)+(.02967*p5)-(.35672*p6)-(.08648*density)+172.20703	0.58	37.15	<0.001	126
CF5RLM	age= (-1.20701*p1)+(.24515*p2)+(.89572*p5)-(2.22554*p6)-(0.02318*density)+105.4291	0.41	9.15	<0.001	52
CF5RLF	age= (-2.9538*p1)+(1.9213*p2)+(1.0153*p3)-(.3511*p5)+(.5283*p6)-(0.1718*density)+267.6572	0.73	34.00	<0.001	67
CF5RMF	age= (-3.44728*p1)+(.43323*p5)+(.04654*p6)+82.806229	0.55	28.36	<0.001	62
CF5RF	age= (-4.2967*p1)+(.9963*p6)+82.806229	0.71	46.99	<0.001	34
CF5RM	age= (0.69868*p5)-(0.62192*p6)-(0.16167*density)+251.9457	0.42	7.82	<0.001	25
CF5LMF	age= (-1.90468*p1)+(.58445*p3)-(.9392*p6)-(0.02314*density)+103.808	0.56	21.36	<0.001	61
CF5LF	age= (-2.8609*p1)+(2.3382*p2)+(2.1841*p3)-(1.1597*p5)-(0.177*density)+273.1288	0.67	15.78	<0.001	31
CF5LM	age= (-0.7792*p1)+(2.1385*p5)-(4.2219*p6)+82.6165	0.51	10.58	<0.001	25

Table 7. Best models for each demographic group (DG) based on male, female, left, and right. CF5 denotes the correction factor of 5. R, L, M, and F denote right, left, male, and female, respectively. For example, RM used data specific to the right os coxa from male individuals for the model creation.

Because some of the demographic variations equated to smaller sample sizes, the all-encompassing model CF5RLMF was tested on the different combinations of male/female and right/left from the test sample. Table 8 shows the top models for each demographic variation.

DG	Model	Adj. r^2	F statistic	p-value	df
CF5RLMF	age= (-1.97674*p1)+(1.03023*p2)+(.02967*p5)-(.35672*p6)-(.08648*density)+172.20703	0.58	37.15	<0.001	126
CF5RLM	age= (-0.33917*p2)+(0.61482*p5)-(1.11392*p6)-(0.10879*density)+192.4948	0.57	44.91	<0.001	127
CF5RLF	age= (-2.17338*p1)+(1.07859*p2)-(0.20136*p5)-(0.08568*density)+171.6184	0.58	46.75	<0.001	127
CF5RMF	age= (-1.5397*p1)+(0.14976*p5)-(0.08098*density)+165.8938	0.58	62.1	<0.001	128
CF5RF	age= (-2.674*p3)+67.581	0.49	127.3	<0.001	130
CF5RM	age= (-1.33*p1)+(0.41812*p5)-(0.44468*p6)-(0.08224*density)+166.9475	0.58	46.35	<0.001	127
CF5LMF	age= (-1.97674*p1)+(1.03023*p2)+(.02967*p5)-(.35672*p6)-(.08648*density)+172.20703	0.58	37.15	<0.001	126
CF5LF	age= (-2.23899*p1)+(0.16853*p2)+(1.59807*p3)-(.82412*p5)-(.08448*density)+172.6275	0.58	37.93	<0.001	126
CF5LM	age= (0.50005*p5)-(1.207*p6)-(.11551*density)+199.4257	0.58	60.23	<0.001	128

Table 8. Best models for each demographic group (DG). The models created for each demographic group used all data and the models were tested with specific demographic groups.

The best models were selected based on the Ryy^2 value, Root Mean Square Error (RMSE), and the how many times the model was able to predict age within 10 years for the test sample of 31 scans or 62 os coxae. Table 9 illustrates the Ryy^2 of each model when applied to the test sample. The performance of the model was deemed "good" if the Ryy^2 value was higher than the adjusted r^2 value of the model. All the best models produced a Ryy^2 value higher than the model adjusted r^2 value. Table 10 shows the best models and their associated RMSE and performance data.

	Performance Based on Ryy^2			
DG	Model	Modern Test Sample	p-value	df
CF5RLMF	age= (-1.97674*p1)+(1.03023*p2)+(.02967*p5)-(.35672*p6)-(.08648*density)+172.20703	0.66	<0.001	61
CF5RLM	age= (-1.20701*p1)+(.24515*p2)+(.89572*p5)-(2.22554*p6)-(0.02318*density)+105.4291	0.73	<0.001	35
CF5RLF	age= (-2.9538*p1)+(1.9213*p2)+(1.0153*p3)-(.3511*p5)+(.5283*p6)-(0.1718*density)+267.6572	0.66	<0.001	29
CF5RMF	age= (-3.44728*p1)+(.43323*p5)+(.04654*p6)+82.806229	0.72	<0.001	30
CF5RF	age= (-4.2967*p1)+(.9963*p6)+82.806229	0.70	<0.001	14
CF5RM	age= (0.69868*p5)-(0.62192*p6)-(0.16167*density)+251.9457	0.75	<0.001	17
CF5LMF	age= (-1.90468*p1)+(.58445*p3)-(.9392*p6)-(0.02314*density)+103.808	0.60	<0.001	30
CF5LF	age= (-2.8609*p1)+(2.3382*p2)+(2.1841*p3)-(1.1597*p5)-(0.177*density)+273.1288	0.80	<0.001	14
CF5LM	age= (-0.7792*p1)+(2.1385*p5)-(4.2219*p6)+82.6165	0.76	<0.001	17

Table 9. Best models for each demographic group (DG) and the corresponding correlation of age prediction to true age of the test sample of 31. Null hypothesis for p-value was no correlation existed between the prediction age and true age.

DG	RSME	Years Difference between Predicted Age and True Age						% Predicted	
		0-0.99	1-4.99	5-9.99	10-14.99	15-19.99	20+	Within 5 Years	Within 10 Years
CF5RLMF1256d	13.62	2	16	12	13	9	10	29	48
CF5RLM1256d	14.65	0	10	5	8	4	9	28	42
CF5RLF12356d	13.76	1	5	8	10	1	5	20	47
CF5RMF156	12.37	1	7	9	4	6	4	26	55
CF5RF16	13.11	0	4	4	4	1	2	27	53
CF5RM56d	12.31	1	5	5	2	3	2	33	61
CF5LMF136d	15.08	1	4	9	6	4	7	16	45
CF5LF1235d	10.50	0	7	2	3	3	0	47	60
CF5LM156	15.85	2	3	4	3	1	5	28	50

Table 10. Best models from each demographic group (DG) and their associated root mean squared error and the prediction performance based on the difference of prediction age and true age. The numbers and the letter "d" in the DG column represent the points that were included for that particular model and if density (d) was also included.

Since my end goal was to apply a quantitative model to a mummy sample, the models generated in this study were tested against a mummy sample. The mummy sample contained 17 individuals with an age range of 16-95 years, with 15 of the 17 mummies ranging between 26 and 55 years of age. Key issues in applying these age estimation models to a mummy sample are the density and correction factor. Bone density in the mummies is significantly reduced compared to the 66 scans from the modern sample used for model development. Density in the 17 mummies ranged from approximately 35 to 715 compared to the modern sample where densities ranged from approximately 900-1500. Consequently, the density variable that worked well in most models could not be applied to the mummy sample because of the low density values; however, the correction factor could still be used. The same scale for correction factor that was used in the modern sample was transposed to the range of the mummy sample. Thus, a correction factor of -5, 5, 10, 15, or 20 mm was applied to individuals with densities between 0-99, 100-199, 200-299, 300-399, and >400, respectively. Because the density range had to be transposed, the best model excluding density and correction factor was tested as well (Tables 11 and 12).

DG	Model	Model Data				Performance Data		
		Adj. r^2	F Statistic	p-value	df	Ryy^2	p-value	df
CF5RLMF1256	Age = (-3.0568*p1)+(*0.5963*p2)-(0.1424*p5)-(0.2076*p6)+80.4201	0.56	42.86	0.00	127.00	0.56	<0.001	16
RLMF1	Age = (-1.704*p1)+66.349	0.00	1.30	0.22	130.00	0.55	<0.001	16

Table 11. Best mummy performance with mummy sample. Best model (CF5RLMF1236) that uses a correction factor but not density in the model. RLMF1 is the best model produced that does not include a correction factor or density measurement. The associated model data and performance data based on Ryy^2 are also shown.

DG	RSME	Years Difference between Predicted Age and True Age						% Predicted	
		0-0.99	1-4.99	5-9.99	10-14.99	15-19.99	20+	Within 5 Years	Within 10 Years
CF5RLMF1256d	15.52	3	6	10	6	3	6	26	56
RLMF1	11.52	7	6	8	5	5	3	38	62

Table 12. Best mummy performance with mummy sample. Best model (CF5RLMF1236) that uses a correction factor but not density in the model. RLMF1 is the best model produced that does not include a correction factor or density measurement. The performance data are also listed for each model in terms of RMSE and years difference between predicted age and true age of the mummy sample.

Because studies have shown that a multi-method approach produces more accurate age estimations (Bedford et al, 1993; Lovejoy et al, 1985), this study took an average of the age predictions from the best models for the right and left sides of the same individual. Table 13 shows that there was as increase in the correlation to true age. This result was found for both the modern test sample and the mummy test sample.

Modern Test Sample								
DG	Performance Before Averaging Right and Left				Performace After Averaging Right and Left			
	Ryy^2	RMSE	p-value	df	Ryy^2	RMSE	p-value	df
CF5RLMF1256d	0.66	13.62	<0.001	61	0.69	13.21	<0.001	30
CF5RLM1256d	0.73	14.65	<0.001	35	0.74	14.35	<0.001	17
CF5RLF12356d	0.66	13.76	<0.001	29	0.69	12.98	<0.001	14
Mummy Test Sample								
DG	Performance Before Averaging Right and Left				Performace After Averaging Right and Left			
	Ryy^2	RMSE	p-value	df	Ryy^2	RMSE	p-value	df
CF5RLMF1256	0.56	15.52	<0.001	33	0.59	14.63	<0.001	16

Table 13. Changes in performance when predicted ages for the right and left os coxa were averaged and then correlated to true age. An increase in Ryy^2 and a decrease in RMSE (narrowing the 95% confidence interval) were observed when the predicted right and left ages were averaged for all models.

Discussion

The results from this study show that simple measurements acquired through the use of post CT processing software can be utilized to estimate chronological age. The best overall model (CF5RLMF1256d) included a correction factor, points 1, 2, 5, and 6, and bone density for both sides and both sexes. The same model without the density estimator also performed well when predicting age at death of a mummy sample. This particular study shows good preliminary results, but there are aspects of the study that need to be considered.

The sample size was large, but an even larger sample could be beneficial to creating a better model. The model which included both right and left os coxae and both sexes had the highest sample size of 132. Some of the other models, such as the model for left male os coxa, had a sample size of only 28. This is problematic because sample size analysis revealed that a sample size of about 60-80 os coxae was needed to see a plateau in the standard error because of the variation observed between individual auricular surfaces. Thus, a sample size of 28 is not sufficient to account for the variation seen in the sample of 132 os coxae.

The sample also was not ideal because the sample ages were bias towards individuals 70-100 years of age. This meant that ages below 70 were not as accurately estimated compared to those individuals 70 and older. A sample with a more even distribution of ages could improve the resulting model. It must be noted that even though the age distribution was not ideal, when the best model was applied to the test sample, which had an even distribution of ages, the goodness of fit was still good even with the variation that was presented between each auricular surface.

Variation in auricular surfaces and shapes was problematic for this study. Each auricular surface was unique, which created difficulties in judging where to place points (Figure 9). The variation in the surfaces resulted in five points that could not be consistently and reliably reproduced by different observers. However, it was possible to reproduce the other 5 points, which could be due to the location of the points in areas where variation was limited. Variation could be the result of many factors such as lifestyle, diet, height, and/or ancestry, just to name a few.

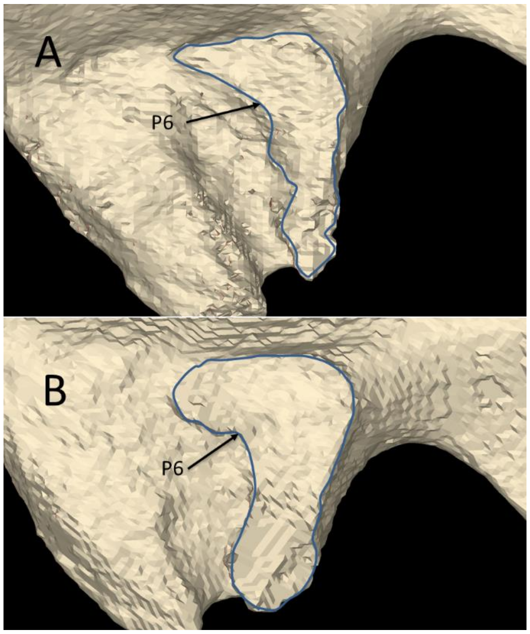

Figure 9. Auriculars surface irregularity. An example of variation between auricular surfaces from individual to individual. Individual A is an auricular surface of a 42 year old female which can be compared to a 45 year old female in B. Notice how distinct P6 is in individual B compared to individual A.

One other factor that could have potentially affected the model is the scan parameters. The scan slice thickness ranged from 0.6 mm to 3 mm, and the larger slice thickness increased the difficulty of identifying the points of interest on the auricular surface. Figure 10 illustrates how much data is lost when slice thickness increases from 0.6 mm to 3 mm. It would have been more ideal to have had all scans with slice thickness under 1 mm to avoid losing detail that is needed to identify location for critical surface points.

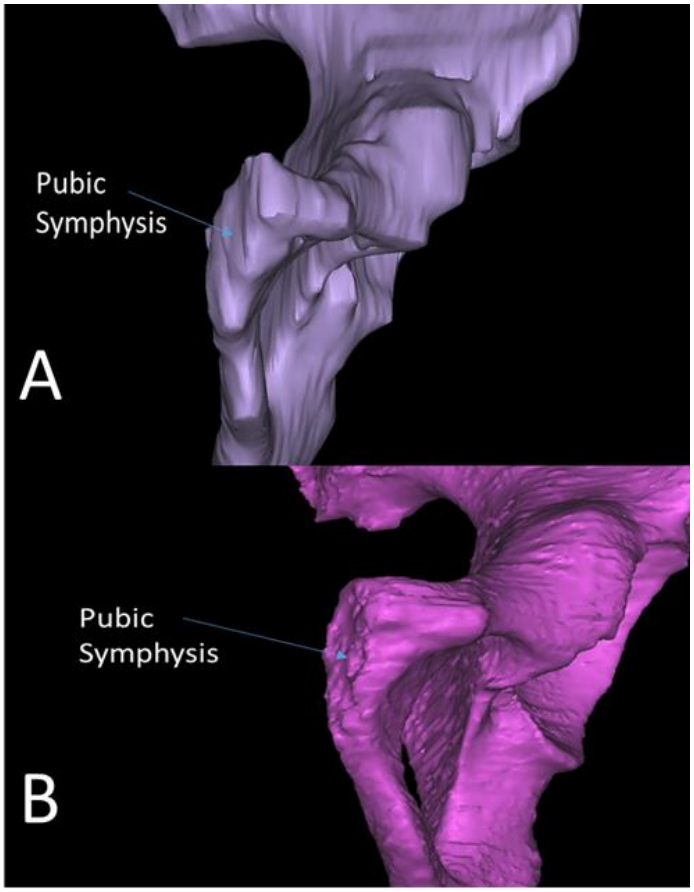

Figure 10. Virtual model comparison with different scan parameters. Picture A and B are of the same individual. Slice thickness for Scan A was 3 mm and slice thickness for scan B was 0.6 mm. Notice the increase in definition from scan A to scan B.

The last aspect of the study that needs to be considered is applicability of the best model to estimating age at death for mummies. If only the point measurements are used, then the study could easily be applied to a mummy sample; however, using just the points does not yield as good a model for estimating age compared to the model that includes density. The one model that used the points was RLMF1, which used just P1 because that was the best model produced. The p-value of the model (p=0.27) shows that the model correlation could be due to random chance; nonetheless, when applied, it predicted ages that had a significant correlation to true age for both the modern and mummy test samples.

The most reliable and effective models were produced when the correction factor based on the bone density was added. The model in its current state is more applicable for modern skeletal material, and it is not as directly applicable to mummy skeletal material. However, some success was reached when transposing the correction factor to the density range of the mummy test sample. Additionally, some improvement was found when age estimations of the right and left side were averaged; however, could averaging the measurements before model creation produce a more effective model?

For this method to be more effective for mummies, a large sample of mummies needs to be acquired and measured, similar to the modern scan sample used for this study. It would then be possible to test whether a similar model applied to mummies is valid. The preliminary results show that measurements that target the depth of the auricular surface can lead to models for estimating age at death. More trials with larger sample sizes and more observers could help validate this method for age estimation.

FUTURE DIRECTIONS FOR RESEARCH

This dissertation covers two important topics that are essential to the improvement of research conducted on mummies: the use of age at death methods with mummies and the use of age at death methods with virtual models. In addition, three questions are addressed in this dissertation: (1) What methods are commonly used to estimate age at death of mummies?, (2) Is it possible and/or appropriate to apply commonly used methods to estimate age at death from virtual models of mummies?, (3) Should new methods be created to estimate age at death from virtual models?

Paper 1 examined the methods used to estimate age at death of mummified individuals. The results in Paper 1 suggest that similar methods are used by many forensic anthropologists in modern settings. Some of the modern methods have also been validated for use with CT imaging; however, if one examines the diversity of methods that was used across the sample of mummy cases, studies suggest that mummy researchers are not in agreement to what methods should be used. This can be problematic for all researchers in their efforts toward consistency in gathering reproducible age at death data. Research findings also show that a multi-method approach provides better accuracy when estimating age at death. When examining recent mummy case studies, there was an obvious lack of consistency in which methods should be used in relation to mummies and CT imaging. Also, few mummy case studies used a multi-method approach. It was observed that best practices had not been used when examining mummies in many of the case studies that were selected. More research is necessary to accumulate data that will determine what best practices encompass. Currently, many researchers are assuming incorrectly that old methods can be used with CT imaging. Research is needed in creating more age at death methods that can be used solely with post CT image-processing software. In order to answer the question of how mummy research can improve age at death data resulting from CT imaging, this study examined the current evidence. Telmon et al (2005), Villa et al (2013), and Dedouit et al (2008) have shown that features can be clearly produced by a virtual model. However, just two methods are not sufficient to support the concept of a multi-method approach to enhance accuracy. Thus, more research needs to focus on collecting data to verify or validate more methods for use with virtual models.

Research that tests existing age at death methods should contribute to the next phase of study. Scan parameters have a significant effect on how the virtual model will appear. Even though Telmon et al (2005) and Villa et al (2013) have shown features of the pubic symphysis can be recreated in a virtual model, many of the mummy scans in the mummy case studies sampled in Paper 2 did not use the same scanning parameters. Inconsistency between scan parameters was present across all the mummy case studies. More research needs to focus on identifying what scan parameters are needed in order to collect accurate data from mummies. Since mummies come in such diverse forms, optimal scan parameters may vary between mummies. For example, mummies preserved in peat bogs in northern Germany may require different scan parameters than mummies preserved in mummy bundles in South America. A consistent protocol of optimal scan parameters and acceptable radiation levels needs to be developed to enhance the amount and type of data produced from a scan, while also protecting the specimen.

Paper 2 identified what methods were being used and focused on comparing the accuracy of commonly used methods with quantitative methods and methods that utilize CT imaging. The goal was to determine whether qualitative or quantitative methods are better at estimating age at death. Much of the available post CT processing software allows for easy quantitative measurements. The hypothesis for this study is that quantitative measurements should be more accurate than observation of qualitative features.

Results revealed that quantitative methods were more accurate when estimating age at death of mummies. The measurements were also more easily reproduced by multiple observers than the ratings of qualitative features; however, there has been limited use of the measurement capabilities of CT imaging for predicting age at death. Future research must expand the measurements capabilities of CT imaging. The research to create new quantitative methods is important for three reasons. First, most qualitative methods do not transpose from a traditional real bone setting to a virtual model. Currently, many scans do not provide the necessary detail to see some skeletal features. Second, many qualitative methods rely on the texture of some features. Current technology enables virtual models to be 3D printed, but not with the fine textures of the real bone. Lastly, there is a discrepancy between experienced and un-experienced observers when using qualitative methods.

With data showing that quantitative methods are generally better for age estimations when using virtual models, Paper 2 reinforces the data with the creation of a quantitative method or model for age estimation. The quantitative method in Paper 3 targeted the change on the auricular surface as an individual ages. The auricular surface is situated low, creating a rim around the surface, and as an individual gets older the height between the surface and the rim decreases. Using the xyz coordinates of the virtual model produced from post CT scan processing software, the height of the rim above the surface could be quantified.

In Paper 3, modern CT scans were analyzed, including bone density. Bone density in ancient bone specimens, e.g., mummies, is problematic because it is much more variable than the bone density in modern specimens. By applying the correction factor to the mummy sample, density values produced accurate age at death estimations for the mummies. It would be beneficial to produce an auricular surface model with just a sample of mummies, because variables such a bone quality could be assessed.

Even though 97 scans were used in the auricular study, a larger sample size would have been beneficial, considering the variability between individual specimens. Agreement between observers was acceptable for five points measured on the auricular surface; however, multiple observers could not reproduce 5 other points. More research is necessary to review whether more points could make the model better and how to select and mark points that are more reproducible. Again, the variability of the auricular surfaces caused much of the discrepancy between observers for the 5 points that could not be reproduced. Potentially, avoiding these areas could be the answer. Much of the variability could be due to other variables such as sex, height, and/or ancestry. More work should target creation of a model using a large mummy sample of known age at death. This could provide some insight into whether or not rim height in relation to bone density could be used as a good age estimator for a mummy sample.

Until medical imaging advances to the point of producing a virtual model with minimal data loss, it will be necessary to test how virtual models can be accurately used to predict and create a life history of a mummy. This dissertation has shown that in some current cases, virtual models increase inaccuracy for age at death estimations. Future research should also target aspects of mummy studies such as paleopathologies in addition to estimations of age at death.

Current technology provides new research opportunities for mummy investigators. The first advance in mummy research has been the application of medical imaging; however, the mummy research field has advanced little despite improvement in methods through the use of modern technology. Instead, old methods were used on virtual models in hopes of gathering accurate data, and resulted in some methods being transposed accurately, while a majority were not. There is a need to invest more time using technology for the purpose of developing new methods specific for virtual models, and to determine whether or not transposing old methods is a viable option.

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Future Directions for Research

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APPENDIX A. CITATIONS FOR SOURCES OF DATA FOR MUMMY CASE STUDIES

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APPENDIX B. SPECIFICS FOR MUMMY SAMPLE

General Information					
Mummy Name	**Origin**	**Era**	**Preservation Type**	**Collection**	**Origin of Age at Death**
Detmold 2	Chile	674 ± 21 AD	Natural	Lippisches Landesmuseum (Detmold, Germany)	Previously Estimated
M1	Chile	1095 ± 50 AD	Natural	Reiss-Engelhorn-Museen (Mannheim, Germany)	Previously Estimated
M6	East Asia	1798 ± 119 AD	Natural	Reiss-Engelhorn-Museen (Mannheim, Germany)	Previously Estimated
Basel Frau	Egypt	330 ± 65 BC	Anthropogenic	Museum of Natural History (Basel, Switzerland)	Previously Estimated
Basel Mann	Egypt	408 ± 6 BC	Anthropogenic	Museum of Natural History (Basel, Switzerland)	Previously Estimated
Nes-pa-kai-shuti	Egypt	650 BC	Anthropogenic	Lippisches Landesmuseum (Detmold, Germany)	Previously Estimated
Freiherr	Germany	1618-1648	Natural	Sommersdorf Castle (Sommersdorf, Germany)	Documented
Kniestatt	Germany	1618-1648	Natural	Sommersdorf Castle (Sommersdorf, Germany)	Documented
Beer Annamaria	Hungary	1712-1807	Natural	Hungarian Natural History Museum (Budapest, Hungary)	Documented
Borsodi Terezia	Hungary	1768-1794	Natural	Hungarian Natural History Museum (Budapest, Hungary)	Documented
Jozef Nigrovitz	Hungary	1738-1793	Natural	Hungarian Natural History Museum (Budapest, Hungary)	Documented
Michael Orlovitz	Hungary	1765-1806	Natural	Hungarian Natural History Museum (Budapest, Hungary)	Documented
Veronica Orlovitz	Hungary	1770-1808	Natural	Hungarian Natural History Museum (Budapest, Hungary)	Documented
M7	Oceania	1803 ± 113 AD	Natural	Reiss-Engelhorn-Museen (Mannheim, Germany)	Previously Estimated
Delemont Frau	Peru	1300 ± 15 AD	Natural	Musées Jurassien (Delemont, Switzerland)	Previously Estimated
Delemont Mann	Peru	1027 ± 24 AD	Natural	Musées Jurassien (Delemont, Switzerland)	Previously Estimated
M2	Peru	1415 ± 16 AD	Natural	Reiss-Engelhorn-Museen (Mannheim, Germany)	Previously Estimated

Scan Information					
Mummy Name	**kv**	**mAs**	**Pixel Size (mm)**	**Slice Thickness (mm)**	**Slice Increment (mm)**
Detmold 2	120	NA	0.98	1.00	1
M1	80	NA	0.98	1.00	Varied
M6	80	NA	0.98	1.00	Varied
Basel Frau	120	108	0.76	1.00	0.5
Basel Mann	140	87.5	0.88	1.50	Varied
Nes-pa-kai-shuti	120	NA	0.98	2.00	2
Freiherr	120	33	0.98	1.00	1
Kniestatt	NA	NA	1.00	1.50	Varied
Beer Annamaria	NA	NA	NA	NA	NA
Borsodi Terezia	NA	NA	NA	NA	NA
Jozef Nigrovitz	NA	NA	NA	NA	NA
Michael Orlovitz	140	28	0.90	1.50	1.5
Veronica Orlovitz	120	120	0.92	0.60	Varied
M7	80	0	0.98	1.00	Varied
Delemont Frau	120	108	0.86	0.60	0.5
Delemont Mann	120	80	0.95	1.50	1
M2	80	0	0.98	1.00	Varied