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Correlation between chronological age and computed tomography attenuation of trabecular bone from the os coxae

James V. Schanandore[a,*], Jonathan M. Ford[b], Summer J. Decker[b]

[a] Physical Therapy Program, University of Jamestown, 4190 26th Ave S., Fargo, North Dakota 58104, United States
[b] Department of Radiology, University of South Florida Morsani College of Medicine, 2 Tampa General Circle, STC7033, Tampa, Florida 33606, United States

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ABSTRACT

Objective: Fields such as biological anthropology, forensic anthropology, archaeology, and mummy studies have increased the use medical imaging, such as computed tomography (CT), to analyze human remains through virtual examination. When predicting chronological age from virtual anatomy, methods developed on skeletal collections do not always produce accurate age predictions when applied to virtual anatomy. Age estimation methods developed specifically for medical imaging can improve accuracy of chronological age prediction when examining virtual anatomy. The present study examines the relationship between attenuation of trabecular bone from the os coxae and chronological age using CT scanning data.

Materials and Methods: A sample of 324 CT scans of living and cadaveric individuals were randomly selected from a CT scan database and used to identify a correlation between trabecular bone CT attenuation in four regions of the os coxae and chronological age. The four regions included trabecular bone deep to the auricular surface, pubic symphysis, posterior superior iliac spine, and the ischial tuberosity.

Results: Through cross validation, the trabecular bone deep to the pubic symphysis, posterior superior iliac spine, and ischial tuberosity resulted in the best prediction models based on model testing. Model testing identified models with adjusted R2 values of 0.83 and 0.86 for combine male/female bone attenuation and only female bone density, respectively.

Discussion: The resulting models, when used in relation with CT scanning data, provide a quantitative method that predicts chronological age and can be used in situations when remains are recently deceased fleshed individuals.

1. Introduction

1.1. Age estimation

Estimating chronological age using human skeletal material has been a research focus in the fields of biological anthropology, forensic anthropology, and bioarchaeology [1–4]. Methods using the pubic symphysis [5,6], auricular surface [7–9], ribs [10], acetabulum [11,12], teeth [13,14], and cranium [15] have been developed and refined to increase accuracy in age estimation. Many of these methods use qualitative changes in bone structure, though a few utilize more quantitative methods. With advances in medical imaging, like computed tomography (CT), traditional qualitative osteological aging methods, such as using the pubic symphysis or ribs [16–18] can be reproduced using virtual anatomy. While these current methods are more qualitative, this increased use of medical imaging in age analysis [1] is allowing for the development of new quantitative methods. For example, Paewinsky et al. [19] developed a quantitative analysis of pulp to tooth ratio using X-ray images that resulting in precise and accurate prediction models. In addition, CT evaluation also allows for the establishment of databases to conduct studies on larger sample sizes of known individuals.

As individuals age, changes occur in bone and studies have shown that there is an overall decrease in bone density [20]. Pasquier et al. [21] published a study that examined the trabecular bone density in the pubic symphysis and reported a significant correlation to chronological age. Modern medical imaging techniques, such as bone densitometry (DEXA), X-ray and CT, regularly capture bone mineral density measurements from patients. While it is accepted clinically and scientifically that bone density decreases with age, few forensic studies have attempted to link these density changes to age estimation [22,23].

* Corresponding author.
E-mail address: James.schanandore@uj.edu (J.V. Schanandore).

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1.2. DVI

Disaster victim identification (DVI) can be an arduous task for forensic pathologists and anthropologists alike. Unknown remains are often fleshed and fragmentary which present a challenge to the use of traditional osteological methods of analysis. The maceration of remains for the assessment of boney tissue is destructive to any present soft tissue. These destructive methods are not always possible in DVI cases and therefore medical imaging and virtual analyses are providing the opportunity for noninvasive, long-term preservation of evidence and biological assessment. It is now common practice internationally to CT scan DVI remains on site as part of the forensic investigation [24–26]. Other agencies CT scan remains as they arrive to the medical examiner's office. This allows for the immediate analysis of unknown remains in a virtual setting.

In the science of estimating age-at-death or chronological age, it is known that multifactorial approaches increase the accuracy of the age estimation [8]. Using modern human data we are able to establish new normal values and methods for the analysis of unknown fresh fleshed remains utilizing the capabilities of medical imaging. The aim of the present study was to determine if the attenuation representing trabecular bone density in multiple regions of the os coxae including the pubic symphysis, auricular surface, ischial tuberosity, and posterior superior iliac spine correlates significantly with chronological age using 3D reconstructions produced by CT data.

2. Material and methods

2.1. Sample

All of the scans used in this study were scanned at [USF Health's Imaging Facilities] on GE Lightspeed 64-slice CT scanners under IRB approval. Due to the clinical nature of the scans, the slice thickness ranged from 0.625 mm to 1.25 mm. Previous study has shown that 1.25 mm is the maximum slice thickness recommended for 3D model reconstruction [27]. The kVp was 120 and mA values were variable depending on the individual case. Each scan was analyzed in the GE standard filter. The selection criteria for the scans were that the complete region of interest was included and all anatomical landmarks to be used in the analysis were visible. Any scan with metal implants, unhealed fractures, or bony changes caused by disease were excluded from this study. Table 1 shows the descriptive statistics of the entire sample. A total of 324 abdominopelvic CT scans were included in this study with known ages with a range of 10–96 years of age. Approximately equal numbers of male and female scans from each decade, e.g. 10–19 years or 20–29 years etc, were included in the sample (Table 1). The sample size was selected to account for the variation of bone density observed across the entire sample. Most of the pelvic region scans were taken with living individuals. In order to increase the age range of the sample, 12 cadaver scans were used for individuals with ages between 90 and 96.

Table 1
Descriptive statistics for the CT scan sample.

Age (Yr.)	Total # of Scans	Male	Female	Min	Max	SD	Average
10–19	31	14	17	10	19	2.44	16.64
20–29	42	19	23	20	29	2.67	23.88
30–39	38	19	19	30	39	2.52	35.36
40–49	37	12	25	40	49	3.08	44.08
50–59	52	27	25	50	59	3.12	54.57
60–69	39	21	18	60	69	2.62	64.84
70–79	37	16	21	70	79	2.88	74.51
80–89	36	20	16	80	89	2.57	83.89
90–99	12	4	8	90	96	1.91	92.83
Sample	324	152	172	10	96	22.86	51.70

2.2. Virtual anatomy reconstructions

Before trabecular attenuation measurements were collected, a 3D reconstruction of the os coxae was used to aid in locating areas of interest for a measurement of Hounsfield Units (HU). The DICOM data from each scan was uploaded into the image viewing and segmentation software package *Mimics Innovation Suite v.19* produced by Materialise in Leuven, Belgium. The reconstructions of the os coxae were produced using a standard bone threshold ($\geq$226 HU) and then manual segmentation was performed to isolate the right and left os coxae. The os coxae models were used to select the landmarks where trabecular HU measurements were made, i.e. pubic symphysis, apex of auricular surface, ischial tuberosity, and posterior superior iliac spine. All modeling was complete by one modeler.

2.3. CT attenuation measurement

The average HU measurement was estimated by using a density measurement tool native to the software. The HU measurement was limited to a square area to select a region of interest (ROI) (Figs. 2,4,6, and 8). Once the ROI was placed, the mean and standard deviation of the region's attenuation in HU was collected. Clinically, HU attenuation from CT has been correlated to bone mineral density (BMD) from DEXA scans [28–30]. That said caution should be utilized as HU values have been shown to change scanner to scanner [31,32]. It must be reiterated that HU is a measurement of X-ray attenuation and not the actual physical density of that object. The size of square ROI used for the present study was a 50×50 mm^2 area. A 50×50 mm^2 square optimized the amount of trabecular bone included while excluding any cortical bone. On few occasions, a 25×25 mm^2 square was used for the pubic symphysis as the 50×50 mm^2 square proved too large and would include some cortical bone, which was often a factor in younger female individuals. It was noted that some individual scans had significantly different densities when comparing the right and left os coxae. Side dominance, environmental effects or other factors could play a role here, however the reason for this difference could not be identified. This observation resulted in averaging the attenuation measurements for the right and left sides of the os coxae for each area measured.

Four areas on the os coxae were targeted for HU measurements: the trabecular bone deep to the mid-pubic symphysis (MPS), apex of the auricular surface (AUR), mid-ischial tuberosity (MIT), and posterior superior iliac spine (PSIS). For the MPS attenuation measurement, the observer would select the middle of the pubic symphysis on the 3D reconstruction. After the selection was made, an independent observer measured the HU within the trabecular bone on the associated 2D axial plane shown in Figs. 1 and 2. The apex of the auricular surface was selected based on Buckberry and Chamberlain [9]. The independent observer would identify and select the apex of the auricular surface and then the associated axial 2D section could be measured for HU value. The placement of the region of interest would be between the cortical bone layers, including the osseous bundle described in Barrier et al. [18] (Figs. 3 and 4). The bundle was included to capture the decrease in density of the bundle as age increases. For the MIT, the independent observer would select the middle region of the ischial tuberosity, which is close to the apex of the ischial bone. Once the selection was made, the ROI would be the trabecular bone within the bulb formed on the associated axial section as shown in Figs. 5 and 6. Lastly for the PSIS, the independent observer selected the apex of the spine and then the ROI would be placed within the deep trabecular bone using the associated axial section (Figs. 7 and 8). These regions of interest were selected for their ease in recognition as sample landmarks for observer reproducibility. The list of potential sample sites is plentiful, and alternates could be used in future directions.