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Review article



Radiocarbon and bomb pulse dating in the forensic context: A systematic review

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ABSTRACT

Radiocarbon analysis in bones, particularly through Bomb Pulse dating, is an essential tool in forensic investigations for estimating the postmortem interval of human remains. However, there are some limitations related to the interpretation of laboratory data, since this can differ from the Post Mortem Interval by many years, depending on the anatomical district and the bone part sampled, as well as the age of the individual and other parameters, since these elements influence bone turnover. In recent years, many studies have been conducted, but with non-standardized data and on limited samples. Therefore there is a need (experienced by the authors themselves in daily forensic practice when only bones are available) to summarize in a single work the data spread in the literature and try to standardize data, as much as possible, with limitation to forensic case only, in a review that is not only critical, but also systematic, in order to have specific and ready to use information for the interpretation of laboratory results. This work, therefore, not only aims to highlight the complexity and the need for standardized methodologies on multiple types of tissue for future research, but also to be an immediate help to refine the interpretation of the results provided by radiocorabion in order to have a Post Mortem Interval as reliable as possible.

1. Introduction

Radiocarbon analysis is an important tool for estimating the postmortem interval (PMI) in forensic investigations involving human remains. PMI also provides important information in the identification process. However, it is influenced by many parameters (age, bone type,

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diet, etc.), and determining PMI requires careful interpretation. Since information in the literature is often non-standardized and based on limited case studies, we highlight the need to standardize data as much as possible to create a practical guide to PMI evaluation.

In general, radiocarbon (^{14}C) analysis is based on the principle that carbon is incorporated into all living organisms through the food chain. After death, the level of ^{14}C in the remains of an organism gradually declines according to the law of exponential radioactive decay with a half-life of 5700 ± 30 years [1]. The radiocarbon age of a sample is calculated by measuring residual ^{14}C concentration in the analyzed tissue. The method can then be used to obtain immediate information about the forensic relevance of the analyzed samples [2]. Since the mid-20th century, this method has been widely used in archaeological research to ascertain the age of numerous samples. In addition to traditional radiocarbon dating, bomb pulse dating involves the analysis of radiocarbon in organic material resulting from the increase of ^{14}C in the Earth's atmosphere during the 1950s and 1960s (with a peak in 1963) when numerous aboveground nuclear tests were conducted [3,4]. Thanks to this increase of ^{14}C in atmospheric CO_2, analyzing the decay of carbon isotopes in organisms assists in estimating the time of death in more recent remains and, consequently, the time since death [5,6]. The technique of bomb pulse dating (using a bomb pulse curve) applies to organisms that lived after 1950 and involves making a direct comparison of ^{14}C levels within human tissues to atmospheric levels to determine the year of tissue formation. Major thermonuclear tests were discontinued in the early 1960s and since then atmospheric radiocarbon levels have gradually declined; current levels are approaching pre-bomb values.

Global atmospheric radiocarbon values exhibited greater variation during the initial rise of the bomb curve than during its subsequent decline [7]. In any case, all organisms that lived after 1950, including humans, are "labeled" with these heightened levels of ^{14}C, enabling the analysis of forensically relevant human remains for estimating the time of death [8].

However, radiocarbon dating requires attentive interpretation since the ^{14}C content of tissues varies depending on factors like age, diet, and type of tissue (because of varying turnover rates). Dating and classifying multiple tissues and different age ranges can help estimate a more reliable range of time of death [9]. The hemisphere in which remains are found can also influence the interpretation of the results [10].

Therefore, in modern research on death date assessments, it is crucial to consider results obtained from various tissues with different radiocarbon values and to compare these estimates with the actual time of death (the difference determines the lag time) [11].

Some authors working in the forensic field have used the bomb peak method to date different types of tissue including teeth, nails, and bones from different anatomical regions or different parts of the same bone (cortical, trabecular, etc.). The rate of bone remodeling in various anatomical regions is another crucial variable in the dating of remains using bomb peak techniques. Since each of these variables can impact the results due to differences in metabolism and cellular turnover, it is important to review what is currently reported in the literature to help establish guidelines for sampling and interpreting ^{14}C laboratory data. The forensic anthropologist is responsible for determining the time since death through careful interpretation of the results.

2. Material and methods

This paper offers a critical and systematic review. It adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring methodological rigor and transparency throughout the process [12].

Registration on PROSPERO was unnecessary as the topic is not related to health and social care.

A systematic search was conducted across three electronic databases, including PubMed, Web of Science, and Scopus. The search strategy was adapted from a PubMed search string, customized for each specific database to ensure comprehensive coverage.

First, we used a specific string adapted for each website, including MeSH terms and all fields:

(((((((("time"[MeSH Terms] OR "time"[All Fields]) AND ("death"[MeSH Terms] OR "death"[All Fields] OR "deaths"[All Fields])) OR ("Post"[All Fields] AND ("mortem"[All Fields] OR "mortems"[All Fields]) AND ("interval"[All Fields] OR "intervals"[All Fields]))) AND ("radiocarbon"[Journal] OR "radiocarbon"[All Fields])) OR "C14"[All Fields] OR ("radiometric dating"[MeSH Terms] OR ("radiometric"[All Fields] AND "dating"[All Fields]) OR "radiometric dating"[All Fields] OR ("carbon"[All Fields] AND "dating"[All Fields]) OR "carbon dating"[All Fields])) AND "Bomb-curve"[All Fields]) OR (("bombs"[MeSH Terms] OR "bombs"[All Fields] OR "bomb"[All Fields]) AND "Peak"[All Fields])) AND ("forensic anthropology"[MeSH Terms] OR ("forensic"[All Fields] AND "anthropology"[All Fields]) OR "forensic anthropology"[All Fields])

Since this review aims to provide tools to identify the most accurate PMI, works were selected that included ^{14}C data from samples of forensic interest, where the anatomical region, lag time, age, and sex were specified. Although included in Table 2, sex was not considered in the analysis since this subdivision of the data would have further reduced the already small sample, compromising any statistical approach.

The *inclusion criteria* for this review were as follows:

1) Must relate to bomb pulse and radiocarbon dating across several fields: forensic anthropology, anthropology, and time-of-death assessment;
2) Must be original research;
3) Must contain at least one of the parameters of interest* ;
4) Must be written in English;
5) Must include bones;
6) Articles taken from the citations of the studies examined must contain at least one of the parameters of interest;
7) Articles must have been published in the last 15 years. The range can be extended by 5 years only if the article includes at least one of the relevant parameters of interest* .

The exclusion parameters established for this systematic review are outlined below:

1) Textbooks;
2) Any articles that do not encompass the topic of radiocarbon dating;
3) Articles related to an archaeological context only;
4) Articles focused only on tissue from different bones;
5) Unavailability of full-text articles;
6) Articles whose data of interest have been included in subsequent works.

*Parameters of interest included: the bone/part of bone analyzed, age, time since death and/or lag time, etc.).

Title/abstract and full-text screening were independently conducted by three researchers using Rayyan AI software [13,14].

The bibliographies of all identified documents were meticulously examined and cross-referenced to identify further relevant studies. A comprehensive methodological evaluation of each document was conducted in accordance with PRISMA standards, including a rigorous assessment of the risk of bias. The data collection process encompassed both study selection and data extraction.

The researchers independently reviewed all papers with titles or abstracts deemed pertinent. Discrepancies regarding the eligibility of works were resolved by consensus. Data extraction was initially performed by three investigators and subsequently verified by a fourth investigator.

3. Results

Twelve articles were initially identified and processed: 6 from PubMed; 3 from Scopus; and 3 from Web of Science. We also included an article identified using the citations analyzed in the previous papers and 3 more from other sources to give a total of 16 papers.

We removed 2 duplicates before screening the remaining 14 articles according to the inclusion and exclusion criteria. Four articles were excluded. The remaining 10 articles were included in the systematic review, as described in Fig. 1. Eight of these were original works, and 2 were review articles.

Three studies were conducted in Washington, D.C., USA, 1 in the USA and Sweden, 1 in Portugal, 1 in the Czech Republic, 1 in Brazil, 1 in Switzerland, and 2 in Australia.

The studies examined a diverse range of samples from various subjects. Cardoso et al. analyzed only one bone sample (cortical and trabecular) from a female subject 16–24 years [15]. This was initially considered to be a case of forensic interest but revealed evidence of a historic clandestine grave (radiocarbon analysis was performed using liquid scintillation). Johnstone-Belford et al. [9,16] investigated hair, nail, and puparia samples collected from 18 subjects; their findings were published in two different papers (2022). In the second article, they analyzed 67 samples from femur and rib fragments including cortical and trabecular bone tissues.

The systematic review included 3 studies by Ubelaker et al. who analyzed: 39 bone samples from 39 individuals (2015) [11]; 68 bone samples from 17 Brazilian subjects, including fragments from femoral, occipital, parietal, and vertebral bones (2022) [17]; and teeth and bone fragments from 7 subjects including cortical fragments from the femur and trabecular bone tissue from the lumbar and thoracic vertebrae [18]. O'Reilly et al. collected two bone fragments from the rib and femur in one individual [19].

Of the 10 studies, 5 used only bone remains, 1 used both bone and teeth, 1 used hair, nails, and puparia, and 1 considered only teeth. Among the studies conducted on bone, 3 focused only on the femur (including the one also conducted on teeth and one review study); 1 included the femur, the flat bones of the skull (parietal and occipital bones), and the vertebral body; and 2 studies involved the use of both the femur and ribs. Regarding the studies conducted on the bone matrix, 3 involved the analysis of both cortical and trabecular bones, 1 involved cortical bone only, and the others did not specify.

Regarding the technology used, 8 papers used the techniques of Accelerator Mass Spectrometer (AMS) and bomb pulse dating, while only 1 paper was based on liquid scintillation (for radiocarbon analysis) using the CALIbomb program.

As for the parameters of interest, 2 studies considered the year of death [15,19]; 2 included the year of death and the year of birth [9,18]; 1 took into consideration the year of birth only [7], 1 the year of death and lag time [11], 1 the year of birth, the year of death and the lag-time [16]; and finally, 1 considered lag time only [17]. Seven studies focused on post-1950 samples [7,9,11,16,17,20,21], two studies analyzed samples before and after 1950 [18], [19], and 1 study analyzed samples dating from the period 1720–1819 and therefore not of forensic interest [15].

All the authors included in this systematic review highlighted that time-since-death estimation is challenging because trabecular and

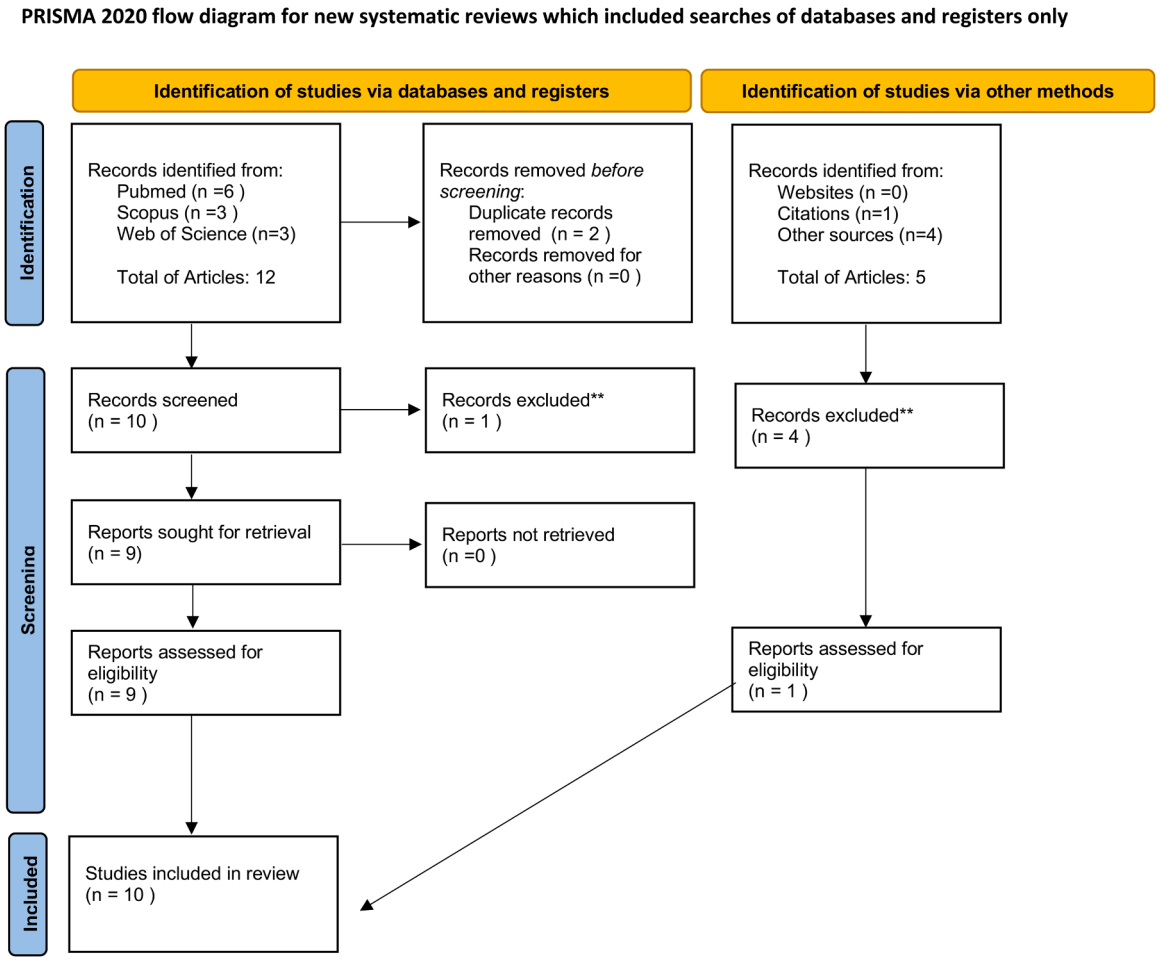


Fig. 1. PRISMA 2020 flow diagram for new systematic reviews.

cortical bones have different turnover rates. The lack of large sample populations and standardized data across the papers is problematic. All the data indicate that trabecular bone generally exhibits a shorter lag time compared to cortical bone. Johnstone-Belford et al. [22] obtained a lag time of only 4 years in puparia, indicating the delay between the time of formation and the time of death, but this evaluation is much more complex when based only on bones. Ubelaker et al. [11] summarized the results published by different authors between 2000 and 2015 [2,11,18,20]. Lag times ranged from 3.20 years for younger individuals to 33.59 years for older individuals. As mentioned in the article, some of the data referred to "bones" in general, with no mention of the sampling location or bone type. Therefore, the data obtained were only partially "standardized"; the 2022 publication contained detailed lag times for various bone types and conditions (femur: 29.5 years; occipital: 25.5 years; parietal: 23.5 years; vertebrae: 8 years) with sex differences, showing a lower lag time for females, particularly over 50 years of age.

The data collected by O'Reilly et al. [19] were published in a case report. Lag time was not evaluated but the year of death was estimated by radiocarbon analysis. The paper confirmed the influence of the age at death on the lag time and stressed the importance of sampling different bones from the same individual to exclude possible artifacts. The rationale behind the interpretation of the results and data flow was well explained. Handlos et al. [21] published two case reports on skeletal remains: death had occurred recently (about 2 years before), which meant that the lag time was considered more reliable.

According to Handlos et al., radiocarbon dating for determining the time of death is effective if different tissue samples are analyzed. They categorized samples into two groups based on carbon turnover times [21]: short carbon turnover tissues (hair, nails, and bone fat, which provide relatively accurate time-of-death estimates but may be influenced by external factors like diet or contamination); and long carbon turnover tissues (bone collagen, which has a longer turnover time and provides less precise time-of-death estimates due to variability within and between individuals).

The data collected from Johnstone-Belford et al. [22] and Ubelaker et al. [17] were included in Table 1 due to the scientific relevance of the authors' findings. Alkass et al.'s research [7] was excluded because it was based only on teeth.

Building on the research of Ubelaker et al. [10], we aimed to create the largest sample possible, with as much standardized data as possible, to serve as a basis for future research. We formulated a table (Table 2) by collecting data from Ubelaker et al.[6,11], Handlos et al. [21], Johnstone-Belford et al. [16], and Hedges et al. [23].

Overall, the information used to build this table included the bone sample, type of bone tissue (cortical or trabecular), lag time, intercept range, and age, categorized by sex. A structured analysis provided a comprehensive comparison, resulting in the formulation of distinct tables sorted by bone sample and increasing age, since these pieces of information are usually known when the laboratory report is received. The inclusion of sex as a variable would have allowed for a more nuanced understanding of the variations within these parameters, but the population was too small and, in this regard, more research is needed. In particular, the need for a different evaluation method for female and male populations is suggested by the difference in bone metabolism, above all in women over 50 years old (some hormonal replacement therapies affect bones).

The papers selected for this review underlined that radiocarbon (^{14}C) dating of biological tissues reveals different carbon turnover times, which can reflect dietary changes. For example, increased intake of freshwater or marine fish, as described by Johnstone-Belford et al. and Handlos et al., can affect ^{14}C levels. Thus, the accuracy of time-of-death estimates would be enhanced by combining analyses of various tissue types, also taking into consideration dietary influences [16,21].

In general, the authors agreed that total bone turnover increases with age and lag time can even exceed 30 years in older individuals, but data were contradictory in some cases, and in general, the range was too wide, thereby reducing the investigative utility. To ensure correct interpretation, it was important to summarize the data with particular attention to the type of bone sampled and the different age ranges (plus sex for future analyses), only including cases where these details were specified, as described in Table 2. All the reported cases included individuals whose year of death was known from attested sources. When this parameter was not evident, the case was included only if investigative evidence led to a narrow range. For example, Handlos et al. [21] reported two cases: one individual remained unidentified but the second case was solved. The data from an initial anthropological profile described in the paper (individual no. II: male, 55–65 years; found in February 2016; PMI: 2–10 years) were corrected after the identification as follows: 56–59 years (date of birth: 1957; average age: 57 years), possible death 2014–2015 (probably 2014, last seen December 2013). The remains were found in early 2016. In previous reviews, revision of data was often incomplete or absent.

It is also important to report the lag time (i.e., the interval between the laboratory value (^{14}C) and the actual date of death) because this element helps in interpreting the data.

Data were attentively sorted by anatomical region and tissue type before being analyzed. The following results were obtained.

3.1. Femoral cortical bone

Age varied between 16 and 96 years. Lag time ranged from 3.2 (from an individual aged 16 years) to 59.5 (75 years), but the 96-year-old individual presented a lower lag time: 31.4.

The data were complicated by the presence of very young individuals, distant in age from the population corresponding to other skeletal parts. Studying the distribution of the values, a slightly increasing trend of the lag time with advancing age was noted. This has already been documented in the literature, although there are some contradictory values. The trend curve of the full data was ($y = 0{,}2639x + 14{,}038$) but to compare the data, two subjects under 33 years of age were removed to standardize the sample by age and enable data comparison. The graphic results are reported in Fig. 2.

The sample relating to femoral cortical bone was the largest and showed that lag time increased with advancing age. However, contradictory values suggested that the results were affected by many factors, some of which were unknown in the individuals analyzed and, presumably, not easy to find even by examining the anamnestic data in depth.

The R^2 value was quite low (R^2=0.07), indicating that the variability of the data cannot be clearly explained.

3.2. Femoral trabecular bone

Age ranged from 57 to 94 years. Lag time ranged from 4.0 to 32.5 (for 57 and 59-year-old individuals respectively) but a lower lag time of 21.5 was reported for the 94-year-old.

The data yielded a slightly ascending trend line but it was almost parallel to the x-axis (Fig. 2). There does not appear to have been much variance compared to the cortical component of the same bone. However, the R^2 score was very low ($R^2 = 0.002$).

3.3. Rib cortical bone

Age ranged from 59 to 94 years. Lag time ranged from 8.5 (in the 75-year-old) to 59.5 (88 year-old) but a rather low lag time of 10.5 was reported for the 94-year-old.

The trend curve confirms that lag time increases with age, even if the data are limited, and, even in this case, the R^2 is rather low (0.06) (Fig. 2).

Table 1
Summary of forensic radiocarbon dating studies: sample characteristics, methodologies, and findings.

Authors	Year of publication	Individuals	N.of samples	Type of samples	Details	Method	Sex	Age of individuals	Target	Dating	Scope	Turnover /LagTime	Results	Relevance	Diet
Cardoso HVF et al. [15]	2012	1	1	Bones (C+T)	Femur dx	Liquid Scintillation	F	16–24 yrs.	YOD	1720–1819	Historical	Not evaluated	The case is challenging due to unclear indicators of whether the skeleton is historical, prehistoric, or modern. The absence of modern artifacts and severe post-mortem changes, along with ritual-like burial positioning and enamel hypoplasias, suggest an archaeological context. However, these factors alone do not rule out forensic relevance. Radiocarbon dating of the bone indicates the individual likely died in the 18th or 19th century, supporting the archaeological interpretation rather than a modern forensic case.	Included according to the criteria of exclusion and inclusion	Ndr
Johnstone-Belford et al. [9]	2022	18	38	14 Hair; 11 Nail; 13 Puparia		Accelerator Mass Spectrometer (AMS) BP		58–94 yrs.	YOD, YOB	post−1950	Forensic. 1st Puparia; 2nd hair; 3rd nails	4 y	All samples displayed Carbon−14 levels consistent with modern (post−1950) standards. Puparia had the highest average Carbon−14 content, followed by hair, with nails having the lowest. Calibration results indicated that 71 % of the samples' Year of Death (YOD) dates included the actual YOD, and all samples had Carbon−14 levels within 4 years of the atmospheric levels at the known time of death. The Carbon−14 content in hair, nails, and puparia was similar,	Excluded according to the criteria of exclusion	It points out how the atmospheric CO2 enters the food chain effecting the radiocarbon levels without describing any specific diet

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Table 1 (*continued*)

Authors	Year of publication	Individuals	N.of samples	Type of samples	Details	Method	Sex	Age of individuals	Target	Dating	Scope	Turnover /LagTime	Results	Relevance	Diet
													averaging 1.029, 1.027, and 1.036, respectively.		
Ubelaker et al. [11]	2015	39	39	Bones	Femur et al.	Not known, BP	23 M+ 16 F	F (33–96 yrs.); M (16–95 yrs.)	YOD, Lag Time	post−1950	Forensic. Review looking for Lag Time interval	3.20–33.59	The data reveal that lag time increases with age at death. For individuals aged 10–19 years, lag time is minimal at 3.2 years. It rises to approximately 12 years for those aged 20–39 years, and further increases to 16.8 years for ages 40–49 years and 25.4 years for ages 50–59 years. In individuals aged 60–99 years, lag time peaks at around 31 years, reflecting very slow bone remodeling and potential radiocarbon recycling. Statistical analysis shows no significant difference in lag time between sexes, indicating that age at death is the primary factor influencing radiocarbon lag time.	Included according to the criteria of exclusion and inclusion	The study deals with how radiocarbon values in bone reflect atmospheric levels through food chains but does not explore specific dietary habits or nutritional details of the individuals.
Ubelaker et al. [17]	2022	17	68 (17 ×4)	Bones	Anterior midshaft femur, occipital, parietal, vertebral body	Accelerator Mass Spettrometer (AMS) BP	11 M + 6 F	F (43 – 53 yrs.); M (50–54 yrs.)	Lag Time	post−1950	Forensic.	Lag Time: femur 29.5 y, occipital 25.5 y, parietal 23.5 y, verterae 8 y.	A bomb pulse curve for the Southern Hemisphere was created, showing peak Carbon−14 levels in 1965. Analysis of 68 samples revealed a mean lag time of 20.24 years, with the femur exhibiting the highest median lag (29.5 years) and the vertebra the lowest (8 years). Diagrams confirmed these trends, showing higher lag times for femur samples and lower for vertebra	Brazil samples, Included according to the criteria of exclusion and inclusion	Ndr

(*continued on next page*)

Table 1 (*continued*)

Authors	Year of publication	Individuals	N.of samples	Type of samples	Details	Method	Sex	Age of individuals	Target	Dating	Scope	Turnover /LagTime	Results	Relevance	Diet
													samples. Stratified analysis by sex revealed a tendency for males to have higher lag times, but no significant sex differences were found. Stable isotope ratios of carbon and nitrogen were also measured, with a mean ratio of 3.24.		
Johnstone-Belford et al. [16]	2022	18	67	BONES (femur C+T;RIB C+T)	Femur and ribs (trabecuar and cortical): 36 (Fem T e C9. Ribs 16 C + 15 T)	Accelerator Mass Spectrometer (AMS)	15 M+ 3 F	F (67–94 yrs.); M (59–91 yrs.)	YOB, YOD, lag time	post−1950	Forensic; for Lag Time Interval	Lag Time: C. Femur 38.9 y; T. Femur 25 y; C.Rib 35.1 y; T.Rib 13.1 y	All samples exhibited Carbon−14 levels consistent with modern (post−1950) radiocarbon, confirming their forensic relevance. The Carbon−14 content varied significantly both between and within individuals, reflecting the complexities of bone turnover and its impact on radiocarbon dating. The study found an average lag time of 25.2 years, which aligns with findings from previous research.	Included according to the criteria of exclusion and inclusion	The study mentions diet as a general factor influencing 14 C concentrations in bone collagen but doesn't go into detail about specific diets beyond a general comparison between **pescatarian** and **omnivorous** diets. Specifically: **Pescatarian vs. Omnivorous Diet**: The study mentions that individuals with a pescatarian diet (one that emphasizes seafood) may show lower 14 C levels due to the marine reservoir effect, where marine organisms appear to have older 14 C levels. This is because the carbon cycle in marine environments is slower, leading to different 14 C uptake compared to land-based food sources.
O'Reilly et al. [19]	2023	1	2	1 rib and 1 femur fregment	Femoral Mid-Shaft Cross-Section, including entire cortex	Accelerator Mass Spettometer, BP	F	50–59 yrs.	YOD	1665–1959 (femur); 1959–1987/ 1989 (rib)	forensic; historic	Not evaluated -default Femur + 20 y; Rib + 3	Radiocarbon dating and isotopic analysis were performed on bone samples from around the 1963 bomb peak. By using	Included according to the criteria of exclusion and inclusion	Ndr

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Table 1 (*continued*)

Authors	Year of publication	Individuals	N.of samples	Type of samples	Details	Method	Sex	Age of individuals	Target	Dating	Scope	Turnover /LagTime	Results	Relevance	Diet
													femur and rib bones, each with different carbon turnover rates, researchers calibrated the radiocarbon data using the Northern Hemisphere bomb curve. Stable isotopes of carbon and nitrogen were measured to provide dietary context but had minimal impact on dating. The results indicated possible ages between 1665 and 1949 CE, with the most probable range being 1718–1822 CE. These findings reflect the complexities of radiocarbon dating and the influence of bone turnover and diet.		
Ubelaker et al. [18]	2006	2	7	Bones and Teeth	(C.Femur, T. lumbar vertebra, tooth: 3.3); (C.Femur, T. Thoracic vertebra, Toot: 3.2, 3.3)	Accelerator Mass Spettrometer, BP	F	one is 70 yrs., one is 33 yrs.	YOB, YOD	1925–1995 (one is before 1950, 0ne is post 1950)	research; lag time	5 y in F33 Trabecular, and 38–39 y in both T e C F70	The radiocarbon analysis of eight samples from two individuals showed that dental samples predate the bomb curve, indicating formation before 1950. The bone samples generally contained bomb carbon, except for one cortical bone sample, which showed minimal post−1954 carbon, suggesting a delay in incorporating new carbon. For the individual born in 1925, the trabecular bone formed around 1954, just before death, while the cortical bone's formation was not dated as closely. The	Excluded according to the criteria of exclusion	the paper does not give a detailed account of the individuals' diets, the isotopic data suggest a diet typical for their region and time period.

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Table 1 (*continued*)

Authors	Year of publication	Individuals	N.of samples	Type of samples	Details	Method	Sex	Age of individuals	Target	Dating	Scope	Turnover /LagTime	Results	Relevance	Diet
													second individual, who lived until 1995, had both bone types with bomb carbon values, indicating formation around 1956–1957. These results reflect the average radiocarbon content of the bone collagen and suggest limited new amino acid incorporation in later years.		
Ubelaker et al. [20]	2014									post−1950	General Review		Radiocarbon analysis reveals varying turnover rates across human tissues, with rapid turnover in blood and hair and slower turnover in bones. This variation impacts the accuracy of dating birth and death. Techniques such as analyzing dental enamel and bone collagen can help estimate birth and death dates, particularly when combined with methods like examining fly pupal cases or eye lens proteins. These approaches offer valuable insights for forensic and anthropological studies but require careful consideration of tissue-specific characteristics.	Included according to the criteria of exclusion and inclusion	The paper doesn't provide explicit details about specific diets, it illustrates how radiocarbon analysis can reveal dietary patterns by examining how bomb carbon integrates into different tissues
Alkass et al. [7]	2011	84 + 35	95 + 35	teeth		Accelerator Mass Spectrometer, BP			YOB	post−1950	research	samples 1955–1963 (12)= 1.9 + /- 1.4 yrs; samples post 1963 (66)= 1.3 + /−1.0	In our study of radiocarbon dating for human teeth, we analyzed enamel from various periods and regions. **Teeth formed before the bomb pulse** (n = 17) mostly showed	Excluded according to the criteria of exclusion	The paper outlines regional dietary patterns based on carbon isotope (13 C) levels in tooth enamel: **Sweden:** Lower 13 C values (−14.7) indicate a diet high in C3 plants.

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Table 1 (*continued*)

Authors	Year of publication	Individuals	N.of samples	Type of samples	Details	Method	Sex	Age of individuals	Target	Dating	Scope	Turnover /LagTime	Results	Relevance	Diet
													negative Δ14 C values, indicating they predate the bomb era. Some contamination may have affected results in a few cases. **Teeth formed between 1955 and 1963** (n = 12) had an average error of 1.9 years in dating, with a strong correlation between estimated and actual formation times. **Teeth formed after 1963** (n = 66) had a very small average error of 1.3 years, aligning well with bomb-derived radiocarbon values. Regional differences in 13 C levels were noted, with significant variations across Sweden, Japan + Middle East, and South America. Despite these regional differences, the radiocarbon dating method maintained high accuracy. Overall, the study confirms the reliability of radiocarbon dating for tooth enamel across different periods and regions.		**Japan:** Intermediate 13 C values (−13.5) suggest a mix of C3 and C4 plants. **Middle East:** Slightly higher 13 C values (−13.7) reflect a similar diet to Japan. **South America:** Higher 13 C values (−10.9) indicate a diet rich in C4 plants, like maize.
Handlos et al. [21]	2018	2	12 (6 +6)	Bones and teeth, hair, nails, adipose tissue	C.Femur, T. Femur Lipidis, hair, nails, T. Clavicula, C. Clavicula, Teeth	Radiocardon analysis using CALIbomb program	M	55–65		Post 1950	research; lag time	Bones (18−35)	This pilot study assessed the use of radiocarbon (14 C) dating to determine the time of death from skeletal remains. It found that samples with short carbon turnover times, such as hair, nails, and bone fat,	Included according to the criteria of exclusion and inclusion	Dietary changes, such as increased consumption of freshwater or marine fish, can affect 14 C levels in tissues, influencing dating accuracy.

(*continued on next page*)

Table 1 (*continued*)

Authors	Year of publication	Individuals	N.of samples	Type of samples	Details	Method	Sex	Age of individuals	Target	Dating	Scope	Turnover /LagTime	Results	Relevance	Diet
													provided more accurate estimates of the time of death, while bone collagen, with its longer and variable turnover, was less precise. The study also highlighted the potential of dental samples to estimate the age at death. Overall, the findings suggest that using a combination of different sample types can improve the reliability of time-of-death estimates, though further research is needed to refine these methods.		

Table 2
General information obtained by the analysis of the single paper, divided by authors, sex, age and type of bone studied.

(1)SOURCE	AGE		SEX	TISSUE	BONE	LAG TIME
Ubelaker and Parra [11]	16		M	Cortical	Femur	3,2
Ubelaker and Parra [11]	27		M	Cortical	Femur	11,9
Ubelaker et al. [11]	33		F	Cortical	Femur	18,5
Ubelaker and Parra [11]	44		M	Cortical	Femur	12,0
Hedges et al. [11]	45		M	Cortical	Femur	30,3
Hedges et al. [11]	50		M	Cortical	Femur	33,2
Hedges et al. [11]	56		M	Cortical	Femur	30,3
Ubelaker and Parra [11]	56		M	Cortical	Femur	12,8
Hedges et al. [11]	60		F	Cortical	Femur	30,9
Hedges et al. [11]	60		M	Cortical	Femur	33,1
Hedges et al. [11]	69		M	Cortical	Femur	30,4
Ubelaker et al. [11]	70		F	Cortical	Femur	37,0
Hedges et al. [11]	75		M	Cortical	Femur	30,2
Hedges et al. [11]	80		M	Cortical	Femur	31,3
Hedges et al. [11]	84		F	Cortical	Femur	31,3
Hedges et al. [11]	85		M	Cortical	Femur	29,0
Hedges et al. [11]	87		F	Cortical	Femur	30,3
Hedges et al. [11]	87		M	Cortical	Femur	30,7
Hedges et al. [11]	93		M	Cortical	Femur	30,5
Hedges et al. [11]	95		M	Cortical	Femur	30,4
Hedges et al. [11]	96		F	Cortical	Femur	31,4
Johnstone-Belford et al. [16]	65		M	Cortical	Femur	33,0
Johnstone-Belford et al. [16]	77		M	Cortical	Femur	57,5
Johnstone-Belford et al. [16]	64		M	Cortical	Femur	39,0
Johnstone-Belford et al. [16]	78		M	Cortical	Femur	56,5
Johnstone-Belford et al. [16]	59		M	Cortical	Femur	53,5
Johnstone-Belford et al. [16]	77		M	Cortical	Femur	16,5
Johnstone-Belford et al. [16]	70		F	Cortical	Femur	59,5
Johnstone-Belford et al. [16]	75		M	Cortical	Femur	29,5
Johnstone-Belford et al. [16]	91		M	Cortical	Femur	23,0
Johnstone-Belford et al. [16]	67		F	Cortical	Femur	31,5
Johnstone-Belford et al. [16]	75		M	Cortical	Femur	59,0
Johnstone-Belford et al. [16]	89		M	Cortical	Femur	31,0
Johnstone-Belford et al. [16]	74		M	Cortical	Femur	27,0
Johnstone-Belford et al. [16]	80		M	Cortical	Femur	58,5
Johnstone-Belford et al. [16]	88		M	Cortical	Femur	44,5
Johnstone-Belford et al. [16]	75		M	Cortical	Femur	24,5
Johnstone-Belford et al. [16]	94		F	Cortical	Femur	27,0
Johnstone-Belford et al. [16]	74		M	Cortical	Femur	32,5
Handlos et al. [21]	60	*	M	Cortical	Femur	24,5
Handlos et al. [21]	57	* *	M	Cortical	Femur	33,5
Handlos et al. [21]	57	* *	M	Cortical	Femur	33,0
Ubelaker et al. [17]	50		F	Cortical	Femur	34,0
Ubelaker et al. [17]	51		F	Cortical	Femur	12,0
Ubelaker et al. [17]	50		M	Cortical	Femur	34,0
Ubelaker et al. [17]	51		M	Cortical	Femur	35,0
Ubelaker et al. [17]	51		M	Cortical	Femur	31,0
Ubelaker et al. [17]	51		F	Cortical	Femur	33.5
Ubelaker et al. [17]	53		M	Cortical	Femur	26,0
Ubelaker et al. [17]	53		M	Cortical	Femur	31,0
Ubelaker et al. [17]	53		F	Cortical	Femur	18,0
Ubelaker et al. [17]	53		M	Cortical	Femur	34,0
Ubelaker et al. [17]	47		F	Cortical	Femur	26,5
Ubelaker et al. [17]	43		F	Cortical	Femur	21,0
Ubelaker et al. [17]	54		M	Cortical	Femur	19,0
Ubelaker et al. [17]	54		M	Cortical	Femur	29,5
Ubelaker et al. [17]	54		M	Cortical	Femur	34,0
Ubelaker et al. [17]	54		M	Cortical	Femur	29,5
Ubelaker et al. [17]	53		M	Cortical	Femur	27,0
Johnstone-Belford et al. [16]	65		M	Trabecular	Femur	26,0
Johnstone-Belford et al. [16]	77		M	Trabecular	Femur	28,0
Johnstone-Belford et al. [16]	64		M	Trabecular	Femur	31,0
Johnstone-Belford et al. [16]	78		M	Trabecular	Femur	30,5
Johnstone-Belford et al. [16]	59		M	Trabecular	Femur	32,5
Johnstone-Belford et al. [16]	77		M	Trabecular	Femur	5,5
Johnstone-Belford et al. [16]	70		F	Trabecular	Femur	20,5
Johnstone-Belford et al. [16]	75		M	Trabecular	Femur	25,0
Johnstone-Belford et al. [16]	91		M	Trabecular	Femur	23,5
Johnstone-Belford et al. [16]	67		F	Trabecular	Femur	20,5
Johnstone-Belford et al. [16]	75		M	Trabecular	Femur	20,0
Johnstone-Belford et al. [16]	89		M	Trabecular	Femur	26,5
Johnstone-Belford et al. [16]	74		M	Trabecular	Femur	14,5
Johnstone-Belford et al. [16]	80		M	Trabecular	Femur	22,5
Johnstone-Belford et al. [16]	88		M	Trabecular	Femur	27,0
Johnstone-Belford et al. [16]	75		M	Trabecular	Femur	16,5
Johnstone-Belford et al. [16]	94		F	Trabecular	Femur	21,5
Johnstone-Belford et al. [16]	74		M	Trabecular	Femur	31,0
Handlos et al. [21]	57	* *	M	Trabecular	Femur	4,0
Handlos et al. [21]	57	* *	M	Trabecular	Femur	28,5
Johnstone-Belford et al. [16]	65		M	Cortical	Rib	15,0
Johnstone-Belford et al. [16]	77		M	Cortical	Rib	27,0
Johnstone-Belford et al. [16]	64		M	Cortical	Rib	10,0
Johnstone-Belford et al. [16]	78		M	Cortical	Rib	47,0
Johnstone-Belford et al. [16]	59		M	Cortical	Rib	13,0
Johnstone-Belford et al. [16]	70		F	Cortical	Rib	25,5
Johnstone-Belford et al. [16]	75		M	Cortical	Rib	30,0
Johnstone-Belford et al. [16]	91		M	Cortical	Rib	16,0
Johnstone-Belford et al. [16]	67		F	Cortical	Rib	31,0
Johnstone-Belford et al. [16]	89		M	Cortical	Rib	22,5
Johnstone-Belford et al. [16]	74		M	Cortical	Rib	20,5
Johnstone-Belford et al. [16]	80		M	Cortical	Rib	24,0
Johnstone-Belford et al. [16]	88		M	Cortical	Rib	59,5
Johnstone-Belford et al. [16]	75		M	Cortical	Rib	8,5

(continued on next page)

Table 2 (*continued*)

(1)SOURCE	AGE	SEX	TISSUE	BONE	LAG TIME
Johnstone-Belford et al. [16]	94	F	Cortical	Rib	10,5
Johnstone-Belford et al. [16]	74	M	Cortical	Rib	16,0
Johnstone-Belford et al. [16]	65	M	Trabecular	Rib	11,0
Johnstone-Belford et al. [16]	77	M	Trabecular	Rib	26,0
Johnstone-Belford et al. [16]	78	M	Trabecular	Rib	4,5
Johnstone-Belford et al. [16]	59	M	Trabecular	Rib	11,0
Johnstone-Belford et al. [16]	70	F	Trabecular	Rib	9,0
Johnstone-Belford et al. [16]	75	M	Trabecular	Rib	9,0
Johnstone-Belford et al. [16]	91	M	Trabecular	Rib	15,5
Johnstone-Belford et al. [16]	67	F	Trabecular	Rib	10,0
Johnstone-Belford et al. [16]	89	M	Trabecular	Rib	20,5
Johnstone-Belford et al. [16]	74	M	Trabecular	Rib	5,0
Johnstone-Belford et al. [16]	80	M	Trabecular	Rib	17,5
Johnstone-Belford et al. [16]	88	M	Trabecular	Rib	32,5
Johnstone-Belford et al. [16]	75	M	Trabecular	Rib	7,0
Johnstone-Belford et al. [16]	94	F	Trabecular	Rib	2,5
Johnstone-Belford et al. [16]	74	M	Trabecular	Rib	15,0
Ubelaker et al. [17]	50	F	Trabecular	Vertebra	8,0
Ubelaker et al. [17]	51	F	Trabecular	Vertebra	3,0
Ubelaker et al. [17]	50	M	Trabecular	Vertebra	7,0
Ubelaker et al. [17]	51	M	Trabecular	Vertebra	13,0
Ubelaker et al. [17]	51	M	Trabecular	Vertebra	4,0
Ubelaker et al. [17]	51	F	Trabecular	Vertebra	8,0
Ubelaker et al. [17]	53	M	Trabecular	Vertebra	28,5
Ubelaker et al. [17]	53	M	Trabecular	Vertebra	10,0
Ubelaker et al. [17]	53	F	Trabecular	Vertebra	5,0
Ubelaker et al. [17]	53	M	Trabecular	Vertebra	5,0
Ubelaker et al. [17]	47	F	Trabecular	Vertebra	10,0
Ubelaker et al. [17]	43	F	Trabecular	Vertebra	8,0
Ubelaker et al. [17]	54	M	Trabecular	Vertebra	11,0
Ubelaker et al. [17]	54	M	Trabecular	Vertebra	9,5
Ubelaker et al. [17]	54	M	Trabecular	Vertebra	12,0
Ubelaker et al. [17]	54	M	Trabecular	Vertebra	6,0
Ubelaker et al. [17]	53	M	Trabecular	Vertebra	10,0
Ubelaker et al. [17]	70	F	Trabecular	L Vertebra	39,0
Ubelaker et al. [17]	33	F	Trabecular	T Vertebra	5,0
Ubelaker et al. [17]	51	F	Cortical	Occipital	11,0
Ubelaker et al. [17]	50	M	Cortical	Occipital	8,0
Ubelaker et al. [17]	51	M	Cortical	Occipital	30.5
Ubelaker et al. [17]	51	M	Cortical	Occipital	21,0
Ubelaker et al. [17]	51	F	Cortical	Occipital	25.5
Ubelaker et al. [17]	53	M	Cortical	Occipital	31,0
Ubelaker et al. [17]	53	M	Cortical	Occipital	26,0
Ubelaker et al. [17]	53	F	Cortical	Occipital	6,5
Ubelaker et al. [17]	53	M	Cortical	Occipital	25,5
Ubelaker et al. [17]	47	F	Cortical	Occipital	29,5
Ubelaker et al. [17]	43	F	Cortical	Occipital	21,0
Ubelaker et al. [17]	54	M	Cortical	Occipital	19,0
Ubelaker et al. [17]	54	M	Cortical	Occipital	21,5
Ubelaker et al. [17]	54	M	Cortical	Occipital	26,5
Ubelaker et al. [17]	54	M	Cortical	Occipital	26,5
Ubelaker et al. [17]	53	M	Cortical	Occipital	34,0
Ubelaker et al. [17]	50	F	Cortical	Parietal	17,0
Ubelaker et al. [17]	51	F	Cortical	Parietal	12,0
Ubelaker et al. [17]	50	M	Cortical	Parietal	17,0
Ubelaker et al. [17]	51	M	Cortical	Parietal	27,0

Table 2 (*continued*)

(1)SOURCE	AGE		SEX	TISSUE	BONE	LAG TIME
Ubelaker et al. [17]	51		M	Cortical	Parietal	27,0
Ubelaker et al. [17]	51		F	Cortical	Parietal	25,0
Ubelaker et al. [17]	53		M	Cortical	Parietal	30,0
Ubelaker et al. [17]	53		M	Cortical	Parietal	30,0
Ubelaker et al. [17]	53		F	Cortical	Parietal	13,0
Ubelaker et al. [17]	53		M	Cortical	Parietal	21,0
Ubelaker et al. [17]	47		F	Cortical	Parietal	27,0
Ubelaker et al. [17]	43		F	Cortical	Parietal	24,5
Ubelaker et al. [17]	54		M	Cortical	Parietal	24,0
Ubelaker et al. [17]	54		M	Cortical	Parietal	17,0
Ubelaker et al. [17]	54		M	Cortical	Parietal	22,5
Ubelaker et al. [17]	54		M	Cortical	Parietal	23,5
Ubelaker et al. [17]	53		M	Cortical	Parietal	22,5
Handlos et al. [21]	57	* *	M	Cortical	Clavicula	31,5
Handlos et al. [21]	57	* *	M	Trabecular	Clavicula	3,5
Handlos et al. [21]	57	* *	M	Trabecular	Clavicula	20,0

3.4. Rib trabecular bone

Age ranged from 59 to 94 years.

The lag time ranged from 2.5 to 32.5 (for the 94-year-old and 88-year-old respectively).

The lowest lag time, however, corresponded to the 94-year-old followed by 4.5 in a 78-year-old man.

This was not an isolated case and it reflects how the data collected sometimes showed contradictions. The trend line was ascending but the R^2 value of 0.08 showed weak predictability (Fig. 2).

3.5. Vertebral trabecular bone

Age ranged from 33 to 70 years.

Lag time ranged from 3 (51-year-old) to 39 (70-year-old). A lag time of 28.5 was reported for one of the 53-year-old individuals; in the other three subjects of the same age, this value was 6.7.

A lag time of 5.0 was recorded for the 33-year-old subject.

The vertebral body seemed to best describe the trend of the lag time with respect to age ($R^2 = 0.4$) (Fig. 2). However, there was a great distance (in terms of age) between the first two individuals (10 years) and the last two (16 years). Furthermore, these ages were determined for a single individual. In short, the age distribution of the sample was not homogeneous.

If we eliminated the "distant" data corresponding to the 33—year-old and 70-year-old subjects, the R^2 dropped to 0.02.

3.6. Occipital bone (cortical)

Age ranged from 43 to 54 years. Lag time ranged from 6.5 to 34, both in a 53-year-old.

The oldest individual with the highest lag time (26.5) was 54 years old.

As before, the data yielded a slightly ascending curve showing a weakly increasing trend with an R^2 value of 0.006 (Fig. 2).

3.7. Parietal bone (cortical)

Age ranged from 43 to 54 years and lag time ranged from 12 (51-year-old) to 30 (53-year-old).

The oldest individual with the highest lag time (24.0) was a 54-year-old.

In this case, the results yielded a slightly decreasing trend line but, as before, the R^2 value was 0.008. (Fig. 2).

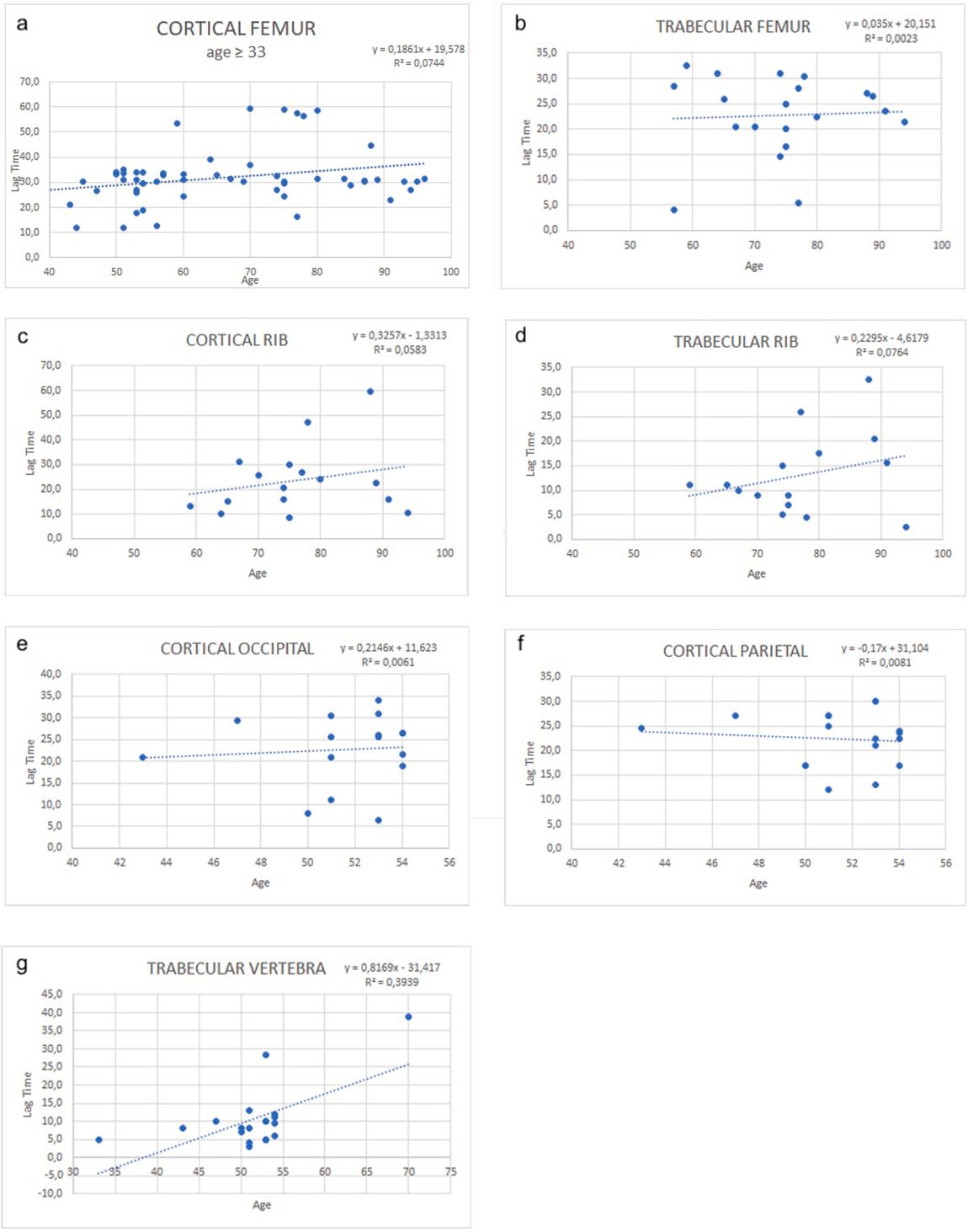


Fig. 2. Trend line and R^2 values based on the dispersion of data about (a) cortical femur, (b) trabecular femur, (c) cortical rib, (d) trabecular rib, (e) occipital bone (cortical), (f) parietal bone (cortical), and (g) vertebral trabecular bone.

4. Discussion

Interpreting radiocarbon dating results in the forensic context (using the bomb pulse technique) requires careful consideration of numerous variables that can significantly influence the accuracy of temporal estimates [11]. Interpretation of laboratory data is the responsibility of forensic anthropologists who must take into consideration the type of tissue sampled, the anatomical region from which it was taken, and whether it is cortical or trabecular, as well as the sex and age of the individual [9,16].

One of the primary strengths of bomb pulse dating lies in its ability to distinguish between pre- and post-1950 samples by leveraging the artificial increase in ^{14}C in the atmosphere due to nuclear testing[9,16, 20]. This technique featured widely in the studies reviewed, with most research focusing on post-1950 samples. However, variability in ^{14}C content across different tissues and individuals complicated data interpretation. This was particularly apparent in comparisons between cortical and trabecular bones, where differences in cellular turnover

rates led to significantly different lag times [17].

The literature on this subject is relatively sparse, and data are not standardized across different studies, making it difficult to provide a comprehensive guide for sampling and interpretation. This challenge is further complicated by the variability of biological material available in each case, such as incomplete and fragmented remains.

Evidence suggests that trabecular bone may be more suitable than cortical bone for these analyses [16]. Vertebrae and ribs yield more accurate time-of-death estimates due to their faster turnover rates. However, in this systematic review, the age range for individuals over 50 years remained quite broad, often exceeding 20 years [19]. Our statistical analysis confirmed that the anatomical region with the fastest turnover rate and lowest lag time was the vertebral body (trabecular), although the R^2 was rather low (0.02). This indicates that the model does not sufficiently explain the phenomenon.

Although estimating the time since death (PMI) is a crucial task in forensic investigations, the statistical analysis involved is not easy, since the required data are limited. Our attempt to statistically approach the data with the aim to predict lag time as a function of age shows that in many cases the correlation was weak and variable (weakly increasing trend of function, low R^2). This suggests that the correlations between the data are not sufficient to formulate useful and reliable predictions and to explain the phenomenon.

Time intervals of a few years would be useful for investigations but defining a short time interval that allows time of death estimation can be risky, because, even in case of individuals not that old, big lag time can be found together with values that are totally contradicted (e.g. 94 years; rib cortical bone; lag time=10.5). Considering the multifactorial nature of bone turnover (also and mainly with female subjects), for individuals older than 45 years considering narrow lag time interval (less than 20 years) must be done with caution.

This is a study that requires an analysis by age groups but in this case a much larger sample is needed. Most of the issues and contradictions would probably be resolved by dramatically increasing the sample. However, this is not simple to do as radiocarbon analysis is expensive and time-consuming.

The reviewed studies highlight that lag time is a critical variable in the interpretation of ^{14}C data. For instance, Ubelaker et al. demonstrated that lag time varies considerably between bone types and also depends on the age and sex of the individual [11,17]. Specifically, trabecular bones tend to exhibit shorter lag times compared to cortical bones due to their higher turnover rates. This was confirmed by Johnstone-Belford et al., who reported significant differences in lag times between cortical and trabecular bones in femurs and ribs [9].

^{14}C analysis can result in more than one range. To identify the correct part of the curve pre- and post-1963 it is necessary to analyze at least two different samples with different turnover rates. Since trabecular and cortical bones have different turnover rates (approximately 25 % and 4 % annually respectively), they contain different levels of ^{14}C [18]. Therefore, the bone type and the relative ^{14}C level determine how ^{14}C results are interpreted [9].

Another layer of complexity arises from the geographical distribution of the sample, with studies conducted in both the Northern and Southern Hemispheres. These geographical differences can influence atmospheric ^{14}C levels and, consequently, the dating of samples. Although most studies focused on samples from the Northern Hemisphere, the global variability in ^{14}C suggests the need to carefully consider the geographical context when interpreting results.

The differences in the samples analyzed represent an additional source of variability. While some studies examined a wide range of tissues, including hair, nails, and teeth, others focused exclusively on bones. This diversity reflects different forensic needs but it makes data interpretation even more complex. Not only can bones be used to estimate the time of death, but tissues with fast carbon turnover rates, such as soft tissues, hair, or nails, can also be considered, as these samples reflect the most recent levels of ^{14}C [24].

Another factor of variation in ^{14}C dating is the influence of diet. Dietary changes over an individual's lifetime, such as increased consumption of freshwater or marine fish, present an intrinsic challenge in accurately interpreting results. Diet is recognized as a relevant factor in ^{14}C dating in the literature [25–27]. However, in the present study, this was addressed in only two analyses. When interpreting results, the potential impact of diet should not be overlooked.

Some non-systematic reviews have examined bomb pulse dating techniques. Although not included in the present study, Johnstone-Belford et al. [22] reported that bomb pulse dating has been successfully applied in forensic cases, including the investigation of war crimes in Ukraine. This technique, when combined with other analyses, such as aspartic acid racemization and isotopic analysis, enhances the accuracy of age-at-death estimates and the determination of geographic origin, particularly in cases involving skeletal remains [22,28]. Furthermore, the same review highlighted that the varying turnover rates of tissues, such as hair, nails, and bones, affect the accuracy of radiocarbon dating. Trabecular bones, with a faster turnover rate, provide more accurate results compared to cortical bones, especially in older individuals whose bone metabolism slows down [26].

A comprehensive analysis of the data confirmed that, theoretically, trabecular bone provides a shorter lag time, making it particularly useful in forensic identification and investigative and judicial inquiries. In particular, the ribs were identified as the most suitable skeletal region when considering subjects over 56 years (an age group considered in all the studies included in this review.

Other skeletal areas (such as the clavicle and vertebrae) are underrepresented, and therefore results may be misleading compared to femur and rib samples, as shown in Table 3. No differentiation was made between male and female subjects to avoid reducing sample size. Also, in cases of mixed and insufficient remains, determining sex is not straightforward. Further examination is necessary, particularly in female subjects as it is well known that in women bone undergoes numerous changes with age, menopause, and endogenous or therapeutic hormonal variations (e.g., hormone replacement or osteoporosis treatments), which could potentially affect dating accuracy.

With the aim to increase the sample, new studies should be performed with careful attention to standardizing data collection and recording all potentially useful parameters, such as sex, age, anatomical region, bone type (trabecular or cortical), the intercept, radiocarbon results, the actual time of death, and/or lag time. Ideally, anamnestic data should also be included but this is not easily available; it is usually derived from skeletal collection only, not case reports.

Finally, radiocarbon analysis and bomb pulse dating offer powerful tools for estimating PMI but they require rigorous interpretation of results in light of the numerous variables that can affect dating accuracy. This paper provides a table with data sorted by anatomical region, bone type, and age. The determination of a contextualized lag time allows forensic anthropologists to correctly interpret data and accurately estimate PMI. Thus, our approach provides a valuable contribution to forensic identification and investigation.

To date, no study has included a large enough population classified by anatomical region, age, and sex. In the papers examined, the samples collected from female subjects were very limited in number. This aspect also deserves further investigation since bone metabolism in women over 50 is problematic, as mentioned earlier.

The literature makes clear that trabecular bone is preferable to cortical bone since it is metabolically more active and therefore has a

Table 3
Data summarized by the age media (>56) and lag time.

Cortical	Femur	75	34,6
Trabecular	Femur	74,3	22,8
Cortical	Rib	76,3	23,5
Trabecular	Rib	77	13,1

faster turnover rate (and returns a shorter lag time). Nevertheless, in the laboratory setting, there are practical issues. Much depends on the context in which skeletal remains are found since this influences the degree of contamination, especially if the bones come from the external environment. Sediment, mold, and roots can often infiltrate trabeculae (more so than cortical bones), making them difficult to separate even with ultrasonic cleaning, and this can affect the results. This is the reason why cortical bone is often chosen.

5. Conclusion

In conclusion, radiocarbon analysis is a crucial technique for estimating PMI in forensic investigations, particularly the bomb pulse dating method. This latter approach to dating human remains leverages the historic increase in atmospheric ^{14}C during a period of prolific nuclear testing, offering valuable insights into the time of death. However, the effectiveness of this technique hinges on a nuanced understanding of various factors, including tissue type, anatomical region, age, and geographical differences. Variability in ^{14}C levels across different tissues and the influence of biological and environmental factors necessitate careful and informed interpretation of results. In our summary of data from different research studies and case reports, sorted by anatomical region and tissue type, the age distribution is not uniform. The data are not sufficient to ensure a reliable statistical analysis of the lag time trends. The range of lag times (and therefore PMIs) is not narrow enough to be useful for investigations. Radiocarbon dating is a valuable method for determining whether or not a sample comes from archaeological remains, but in forensic cases, it can be risky to rely on a narrow lag time even in case of young adults.

Trabecular bone, especially from the vertebral body, seems to have the best turnover rate. In most of the groups analyzed in this study, the data revealed many contradictory values and a low coefficient of determination (R^2). This could be resolved in future studies by increasing the sample. To enhance the accuracy of forensic dating, future research must address these complexities by standardizing methodologies, examining a broader range of tissues, and accounting for demographic and regional variations. By doing so, forensic experts could better harness the potential of radiocarbon dating to provide accurate and reliable time-since-death estimates.

In parallel with these considerations, from a practical point of view, it is important to note that trabecular bone is often subject to contamination by organic material such as roots, mold, sediment, etc., which can affect the results. This is the reason why the cortical bone is more frequently used.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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