Forensic Sciences Research, 2024, Vol. 9, Issue 3
https://doi.org/10.1093/fsr/owae046
Research Article

Application and implications of radiocarbon dating in forensic case work: when medico-legal significance meets archaeological relevance

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Abstract

The estimation of the postmortem interval for skeletal remains is a crucial aspect of forensic anthropology. This paper illustrates the importance of radiocarbon analysis for establishing medico-legal significance and supporting forensic identification, through the analysis of three case studies for which the years of both birth and death were investigated. In Audresselles, Northern France, a partial skull was discovered with no contextual information or identity. Radiocarbon dating yielded an average calibrated calendar age of 4232 BCE (92.5% probability), indicating significant archaeological value but no forensic relevance. In the second case, skeletal remains were found in the flooded underground of a historical fort at Wimereux, Northern France, also with no identity. Radiocarbon dating based on the bomb-pulse curve indicated a calibrated date of death in 1962 CE (37.3% probability) or 1974–1975 CE (58.1% probability), both surpassing the French statute of limitations. Lastly, a skeleton with a suspected identity was discovered near Valenciennes, Northern France, and various biological tissues underwent radiocarbon dating. A bone sample suggested a calibrated date of death of 1998–2002 CE (84.6% probability), differing from a hair sample (2013–2018 CE, 83.3% probability) because of the slower bone tissue remodeling process. DNA analysis confirmed the person's identity, reported missing a decade prior to the discovery of the remains, following the alignment of the radiocarbon results with the individual's year of birth based on dental tissues and year of death. These case studies reveal that traditional radiocarbon dating and bomb-pulse dating are essential tools for estimating the postmortem interval, providing mutual benefits for archaeologists, forensic anthropologists, and the criminal justice system.

Key points

- Traditional radiocarbon dating and bomb-pulse dating are essential tools to establish the archaeological relevance or medico-legal significance of human skeletal remains.
- Bomb-pulse dating enables assessment of an individual's years of birth and death.
- Bomb-pulse dating helps to narrow down the pool of candidates for identification.
- Radiocarbon analysis provides mutual benefits for archaeologists, forensic anthropologists, and the criminal justice system.

Keywords: ^{14}C; bomb-pulse dating; postmortem interval; forensic anthropology; identification

Introduction

Estimating the postmortem interval (PMI), the time elapsed since death, is critical in any forensic investigation, assisting in the investigation of the death, the reconstruction of the surrounding events and timeline, and the identification of the decedent [1]. The precision of PMI assessment decreases with increasing time since death. For a short PMI, forensic pathologists rely on a set of rapid biochemical changes of forensic significance that allow narrower PMI estimations, and a relatively large set of methodological approaches [2–5]. There are fewer methodological approaches for a longer PMI, focusing on the examination of decomposition stages, sometimes using entomological, botanical, or biochemical methods. The efficacy and precision of these methods diminish as decomposition progresses [6–9].

Received: April 23, 2024. **Accepted:** June 12, 2024

The complexity escalates with skeletonized bodies, as visual examination of the bone degradation stages becomes insufficient, and the timing of skeletonization varies significantly depending on a wide range of extrinsic and intrinsic factors [9]. As such, PMI estimation is one of the most challenging parameters in forensic anthropology [1]. The stratigraphic sequence and circumstantial evidence may be pivotal for the PMI estimation of skeletonized remains. Various techniques have been explored to assess the PMI of skeletal remains, including chemiluminescent reactions [10–14], UV–Vis spectroscopy [15–17], UV–Vis-induced fluorescence [18], X-ray diffraction (XRD) [19], Fourier transform infrared (FTIR) spectroscopy [17, 20–23], Raman spectroscopy [22–24], high-performance liquid chromatography–tandem mass spectrometry (HPLC–MS/MS) [25], metabolomics, lipidomics, and proteomics [1, 26], microcomputed tomography [27], and digital imaging or stereomicroscopy [28] (see [9, 29] for reviews). While promising, most of these approaches are still being developed, or have not yet produced sufficiently robust results to meet medico-legal standards [29]. The uncertainty associated with these methods, particularly when remains are extensively degraded, makes them inadequate for establishing whether remains are of archaeological origin or if there is medico-legal significance, which is critical for determining the following investigative process and for forensic identification [29, 30].

In France, crimes carry a 20-year statute of limitations[1] on criminal legal proceedings, with some exceptions (30 years for terrorism-related offenses, organized drug trafficking, eugenics, and war crimes, and no statute of limitations for crimes against humanity). The discovery of human skeletal remains in areas of high archaeological potential triggers legal requirements under both the French Penal Code[2] and the Heritage Code[3]. Over 38 000 archaeological sites are known in Northern France[4], with an average of 350 archaeological interventions each year conducted by 14 archaeological organizations. Moreover, there are hundreds of thousands of fallen WWI soldiers with no known graves. Hence, law enforcement and forensic experts should consider all human skeletal remains without clear historical context as potentially relevant to medico-legal investigations until demonstrated otherwise.

In France, as in many other countries worldwide, the adoption of a technique to establish medico-legal significance or archaeological relevance is critical. The exclusion of medico-legal significance in areas with high archaeological potential will decrease the time and costs associated with other investigative procedures, including the identification process. Radiocarbon dating is a reliable and versatile tool to determine whether skeletonized remains are of archaeological or forensic significance [31–33] and can also estimate a year of death [34, 35]. However, although this method has been well established for decades among geologists, archaeologists, and bioarchaeologists, radiocarbon dating is still underused in forensic anthropology. PMI estimation based on radiocarbon dating meets medico-legal requirements and adheres to various standards, including testability, internationally standardized protocols, long-established error rates, validation through abundant peer-reviewed publications, and broad acceptance within relevant scientific communities.

The radiocarbon isotope (^{14}C) forms naturally by neutron bombardment of stable ^{14}N in the upper troposphere and stratosphere, following the reaction:

$$^{14}_{7}N + \, ^{1}_{0}n \Rightarrow \, ^{14}_{6}C + \, ^{1}_{1}p \tag{1}$$

Upon formation, radiocarbon is oxidized and diluted in the atmosphere. It integrates into all living organisms in continental, freshwater, and marine ecosystems [36, 37], which maintain ^{14}C isotopic equilibrium with the atmosphere throughout their lifetime. Upon their death, the radiocarbon begins to decay radioactively following a β^- disintegration, such that:

$$^{14}C(t) = \, ^{14}C\,(t_0)\, e^{-\lambda t} \tag{2}$$

where t is the PMI, t_0 is the time of death, and λ is the radioactive disintegration constant. Therefore, through measurement of $^{14}C(t)$ with constraints on $^{14}C(t_0)$ and λ, the PMI can be estimated.

Quantifying radiocarbon in samples is challenging because of its scarcity, with typical ^{14}C/^{12}C ratios between 10^{-12} and 10^{-15} [38]. Two main techniques are currently used: β^- counting estimates the number of particles emitted by radiocarbon isotopes using specific counters [39], while accelerator mass spectrometry (AMS) directly measures the number of ^{14}C atoms in a sample and the ^{14}C/^{12}C ratio. Currently, AMS is most often used, because of its efficiency and minimal sample requirements [40]. For each sample, the percent Modern Carbon (pMC, %) can be calculated based on the ratio between the ^{14}C content of the sample and the modern (1950 CE) ^{14}C quantity, assessed from a standard included in the analytical protocol. Using equation (2), the pMC allows a radiocarbon age to be calculated for each sample. However, because of variations in the ^{14}C concentration in the atmosphere over time and space, the relationship between the calculated radiocarbon age and the "true" calendar age of a sample is complex. To account for these variations, sinusoidal calibration curves are regularly produced [41, 42]. The calibration curve used currently in the Northern Hemisphere is IntCal20 [43].

The ^{14}C disintegration half-life period is 5568 ± 30 radiocarbon years [44], and so traditional radiocarbon dating applies to samples ranging from 300–50 000 years [45], encompassing most archaeological material but less relevant for modern remains in forensic contexts. In these cases, the bomb-pulse dating method capitalizes on the temporary spike in atmospheric ^{14}C around 1960, resulting from nuclear testing during the 1950s and early 1960s. The bomb-pulse curve is used to date recent samples, characterized by pMC > 100%, and is thus relevant for medico-legal inquiries [46]. The bomb-pulse calibration curve currently used for the Northern Hemisphere is Bomb21NH1 [47].

Radiocarbon is assimilated by biological tissues throughout their development and remodeling, occurring at varying stages and rates throughout life. For samples characterized by pMC > 100%, analysis of tissues that undergo little-to-no remodeling throughout life, such as dental tissue, reveals the levels from their period of formation, allowing estimation of the year of birth [48, 49]. Tissues with rapid formation or remodeling, such as soft tissues, indicate the year of death [50, 51].

Both traditional radiocarbon and bomb-pulse dating offer valuable insights into the medico-legal significance and identification of human remains, in both forensic and archaeological contexts. We illustrate this assertion here, by presenting three recent case studies from the Forensic Institute in Lille, France, in which this approach contributed to or excluded identification.

Case study 1: Audresselles, France

On 17 June 2017, a partial human skull was discovered on the beach at Audresselles, Pas-de-Calais, Hauts-de-France, France, by law enforcement agents, lacking additional contextual information. The bones were cleaned, arranged anatomically, and photographed (Figure 1). The skeletal remains included the frontal bone, both parietal bones, the right temporal bone, the right maxilla with teeth #13, #14, #16, #17, and #18, and fragments of the sphenoid bone, all belonging to a single adult individual. The skull exhibited taphonomic alterations, including some breakage, abrasion, and striations evenly distributed across most areas of the skull. Black staining was visible on the endocranium and on the external cranial surface. There were some marine organismal adhesions in the external auditory meatus and adjacent areas. No signs of scavenger activity were detected, nor was there evidence of weathering patterns typical of terrestrial environments, such as sun bleaching or uneven weathering of the bone surface. We were unable to determine if the skull underwent immersion in a marine environment or if it was exposed to the shore environment for a short time. However, the skull presented no taphonomic signs of long-term terrestrial surface exposure.

The sex was estimated using morphological traits [52]. The sharp supraorbital margin and the small volumes of the mastoid process and glabella indicated a possible female. The skull belonged to an adult individual, but a more precise age-at-death estimation was not possible. The Lamendin dental root method [53] was attempted and yielded an estimated age at death of 40.0 ± 6.9 years, but this must be taken with caution because of the potential influence of taphonomic factors. No perimortem or antemortem changes were observed.

Considering the lack of circumstantial evidence and the rise in migrant deaths crossing the English Channel from France, the likelihood of medico-legal significance was high. Since none of the existing macroscopic methods allow a reliable and narrow PMI estimation, radioisotope examinations were conducted on a parietal bone sample. Sampling was performed using a mini-drill equipped with a diamond drill bit. Afterwards, the sample underwent a series of processing steps, including crushing, washing with Stakpure™ ultrapure water, and drying in a vacuum oven at 60°C for 24 h. Finally, it was finely powdered using a Pulverisette 7™ planetary ball mill. Radiocarbon dating of bone samples typically targets the organic bone collagen fraction, requiring its extraction from the bulk sample. Bone collagen extraction was performed at the Centre de Recherche et de Restauration des Musées de France (C2RMF), following established protocols adapted from Longin and described by Richardin et al. [54] and Clauzel et al. [55] that involve successive acid and basic solution treatments to remove the bone mineral matrix, followed by filtration and freeze-drying of the collagen.

Radiocarbon dating was conducted using AMS at the Artemis AMS Facility, Saclay, France [56]. Calendar dates were determined using the OxCal v.4.4.4 procedure [41, 42, 57] and calibrated at 95.4% probability using the IntCal20 calibration curve for the Northern Hemisphere [43], considering that marine products only contributed marginally to the individual's diet.

Unexpectedly, the bone samples yielded radiocarbon ages of 5380 ± 30 years before present (BP), 5385 ± 30 BP, and 5395 ± 30 BP, respectively (Table 1, Figure 2). When combining these results, we obtained an average radiocarbon age of 5387 ± 18 BP, corresponding to a calibrated date range of 4332–4168 BCE. This firmly establishes the archaeological origin of the remains and demonstrates no medico-legal significance. This skull is the first Neolithic bone found in this specific area, although some sites from this period have been identified along the Channel coast. The skull could have originated from a submerged site in this area, or from a nearby site with the bones subsequently dispersed by currents. Here, traditional radiocarbon dating was definitive in discriminating between forensic and archaeological contexts, avoiding a time-consuming and costly case investigation and DNA analysis, and the loss of cultural heritage.

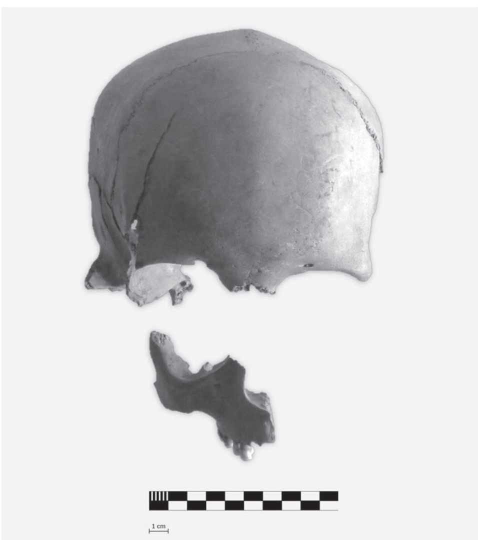

Figure 1 Cranial remains discovered on the beach at Audresselles (France) with no contextual information.

Case study 2: Wimereux, France

In February 2019, human skeletal remains were discovered in the Fort de la Crèche in Wimereux, Pas-de-Calais, Hauts-de-France, France. This fortification has been instrumental for over two centuries because of its strategic location, used in numerous conflicts that faced this region. It was initially built in 1879 as a component of the defense network termed the Séré de Rivières system. The fort was also operational throughout WWI, underwent modernization to evolve into a significant battleground during WWII, and was finally integrated into the Atlantic Wall. It was decommissioned in 2002, but for decades has been frequently occupied by homeless people. The human skeletal remains, alongside nonhuman mammals (cattle and canids), were found in the flooded underground of the fort that had been locked for approximately 15 years. Recovery was carried out by law enforcement agents. Complete water removal was impractical because of the associated challenges and costs resulting from the extensive volume of the flooded rooms. The remains included a pelvis, right and left femurs, a right tibia, and an incomplete right foot (missing two middle and four distal phalanges). The minimum number of individuals was one adult with no identity (Figure 3). No antemortem or perimortem lesions

Table 1. Radiocarbon age and calibrated dates for the human bone sample from Audresselles beach.

Sample	Nature	pMC (%)	Radiocarbon age (BP) (years)	Calibrated dates (2σ, 95.4% probability)
1A1458	Parietal bone	5.170 ± 0.190	5380 ± 30	4334 BCE–4224 BCE (66%) 4200 BCE–4164 BCE (17.2%) 4128 BCE–4111 BCE (2.9%) 4100 BCE–4060 BCE (9.4%)
2A1458	Parietal bone	5.160 ± 0.200	5385 ± 30	4335 BCE–4224 BCE (71%) 4199 BCE–4164 BCE (15.1%) 4126 BCE–4112 BCE (1.9%) 4098 BCE–4062 BCE (7.4%)
2B1458	Parietal bone	5.101 ± 0.197	5395 ± 30	4338 BCE–4227 BCE (80.3%) 4196 BCE–4166 BCE (11.1%) 4095 BCE–4066 BCE (4.1%)
All samples combined			5387 ± 18	4332 BCE–4231 BCE (83.9%) 4194 BCE–4168 BCE (11.5%)

The combination was checked for consistency by a chi-squared test, performed automatically by the OxCal™ system. pMC: percent modern carbon; BP: before present; BCE: before the common era.

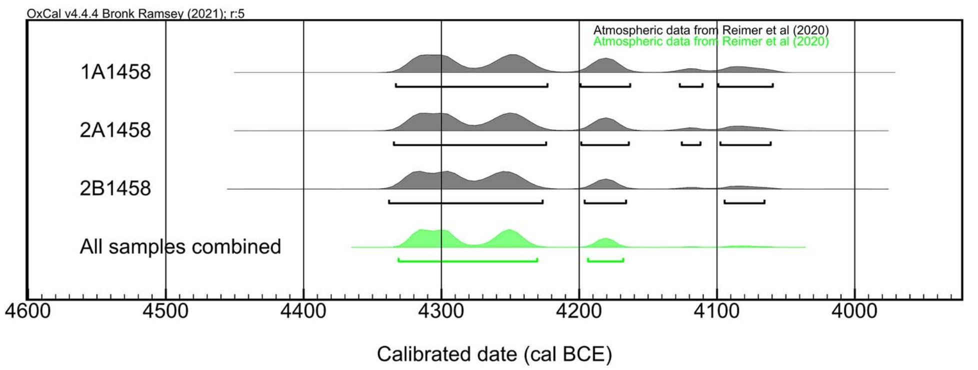

Figure 2 Calibrated dates obtained for the sample from Audresselles (France) using the IntCal20 calibration curve [43]. BCE: before the common era.

Figure 3 Skeletal remains discovered at Wimereux (France).

were observed on the bones. The probabilistic sex estimation was based on metric analysis of the innominate bone [58], indicating a male (probability female (P(F)): 0.00; probability male (P(M)): 1.00). The age at death was assessed based on the morphology of the pubic symphysis following the method developed by Brooks and Suchey [59], and indicated an age range of 19.8–27.0 years (mean, 23.4; standard deviation (SD), 3.6 years) (Phase II).

The bones exhibited macroscopic postmortem modifications, including staining, consistent with prolonged exposure in stagnant water. Visual inspection for PMI estimation was influenced by the prolonged exposure to contaminated water, which altered the appearance. Although the bones appeared relatively recent based on subjective experience, the PMI could not be estimated based solely on these features. Since the site has a history of multiple occupations, from historical periods to contemporary times, the PMI could theoretically range from a few years to a century. To provide additional insights, radiocarbon dating was suggested to the investigating officer and to the magistrate, who approved and officially requested analysis. Femoral cortical bone sampling was performed by the forensic practitioner, and pretreatment and dating procedures were conducted by the C2RMF and the Artemis facility, following similar protocols to those described in the previous case study.

The sample exhibited a pMC value exceeding 100%, indicating a more recent date than 1950 and therefore suitability for bomb-pulse curve dating (Table 2, Figure 4).

Table 2. pMC and calibrated dates for the human bone sample from the Wimereux fortification.

Sample	Nature	pMC (%)	Calibrated dates (2σ, 95.4% probability)
1A1459	Femoral cortical bone	137.630 ± 0.280	1962 CE (5.2%) 1974 CE–1976 CE (90.3%)
2A1459	Femoral cortical bone	136.700 ± 0.290	1962 CE (7.2%) 1975 CE–1976 CE (88.3%)
1B1459	Femoral cortical bone	140.956 ± 0.298	1962 CE–1963 CE (41.5%) 1973 CE–1976 CE (53.9%)
2B1459	Femoral cortical bone	140.420 ± 0.297	1962 CE–1963 CE (45.9%) 1974 CE–1976 CE (49.5%)
All samples combined			1962 CE–1963 CE (14.2%) 1974 CE–1976 CE (81.3%)

CE: common era. The combination was checked for consistency by a chi-squared test, performed automatically by the OxCal™ system. pMC: percent modern carbon.

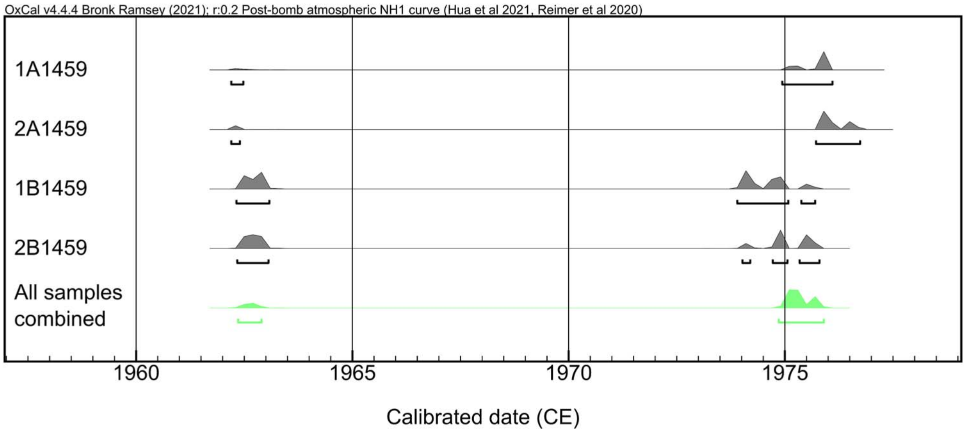

Figure 4 Calibrated dates obtained for the sample from Wimereux (France) using the Bomb21NH1 bomb-pulse calibration curve [43,47]. CE: common era.

The calibrated dates indicated a year of death of either 1962–1963 (14.2% probability) or 1974–1976 (81.3% probability). Even considering a lag time—a difference between the actual year of death and the ^{14}C-estimated year, dependent on the type of bone tissue and the age at death—this indicates that the individual likely died more than 20 years before the skeletal remains were found, precluding the initiation of a judicial procedure in the French legal system. Investigations performed on clothing and a plastic shopping bag found near the skeletal remains supported the likelihood that the individual died during 1970–1980, consistent with the radiocarbon dating. Therefore, radiocarbon bomb-pulse dating of this modern sample indicated a recent PMI but a lack of medico-legal significance under the French judicial legal system. Although investigation for identification purposes may not be legally required after 20 years, radiocarbon dating could aid in narrowing down potential candidates for identification, and, even if not legally mandatory, a sample could still be sent to the Automated National DNA Data Bank. In this case, it was suggested that DNA analysis would be advisable, but no actions were taken by the legal authorities.

Case study 3: Valenciennes, France

In 2022, human skeletal remains were discovered near Valenciennes, Nord, Hauts-de-France, France, during the clearance of overgrown vegetation near a residential area. A well-preserved and nearly complete skeleton was found alongside associated evidence, including clothing, a hair clip with preserved hair, personal belongings, and a health insurance card bearing the identity of a person reported missing in the area 10 years prior to the discovery of the remains.

Biological sex estimation was based on measurement of the innominate [58]. The result indicated a female (DF: 13.02; DM: 35.05; P(F): 1.00; P(M): 0.00). This was supported by measurement of the proximal femur (P(F): 0.70) [60] and examination of cranial morphological features [52]. The age-at-death was assessed based on the pubic symphysis morphology following the method developed by Brooks and Suchey [59]. This indicated an age range between 27.3 and 49.1 years (mean: 38.2; SD: 10.9 years) (Phase IV). The age at death was refined by cementochronology using a lower canine [61], which estimated an age at death ranging from 48–58 years.

No antemortem or perimortem lesions were observed. Postmortem alterations included plant root etching, staining on the skull surface (Figure 5A and D), and rodent and/or carnivore gnaw marks on long bones and ribs (Figure 5H and I). The skull was whitened on the exposed surface and colonized by moss (Figure 5B and G).

These observations suggested a PMI of a few years. Radiocarbon dating was then conducted on two biological tissues, hair and vertebral cancellous bone, to estimate the time since death. Radiocarbon analysis of two teeth was also performed to assess the year of birth.

The samples were sent to Beta Analytics™ (Miami, USA), where they underwent AMS radiocarbon dating. The hair sample was submitted to an acid/alkali pretreatment, while soluble collagen extraction protocols were applied on both the tooth and bone samples. AMS measurements were conducted directly in the company laboratories.

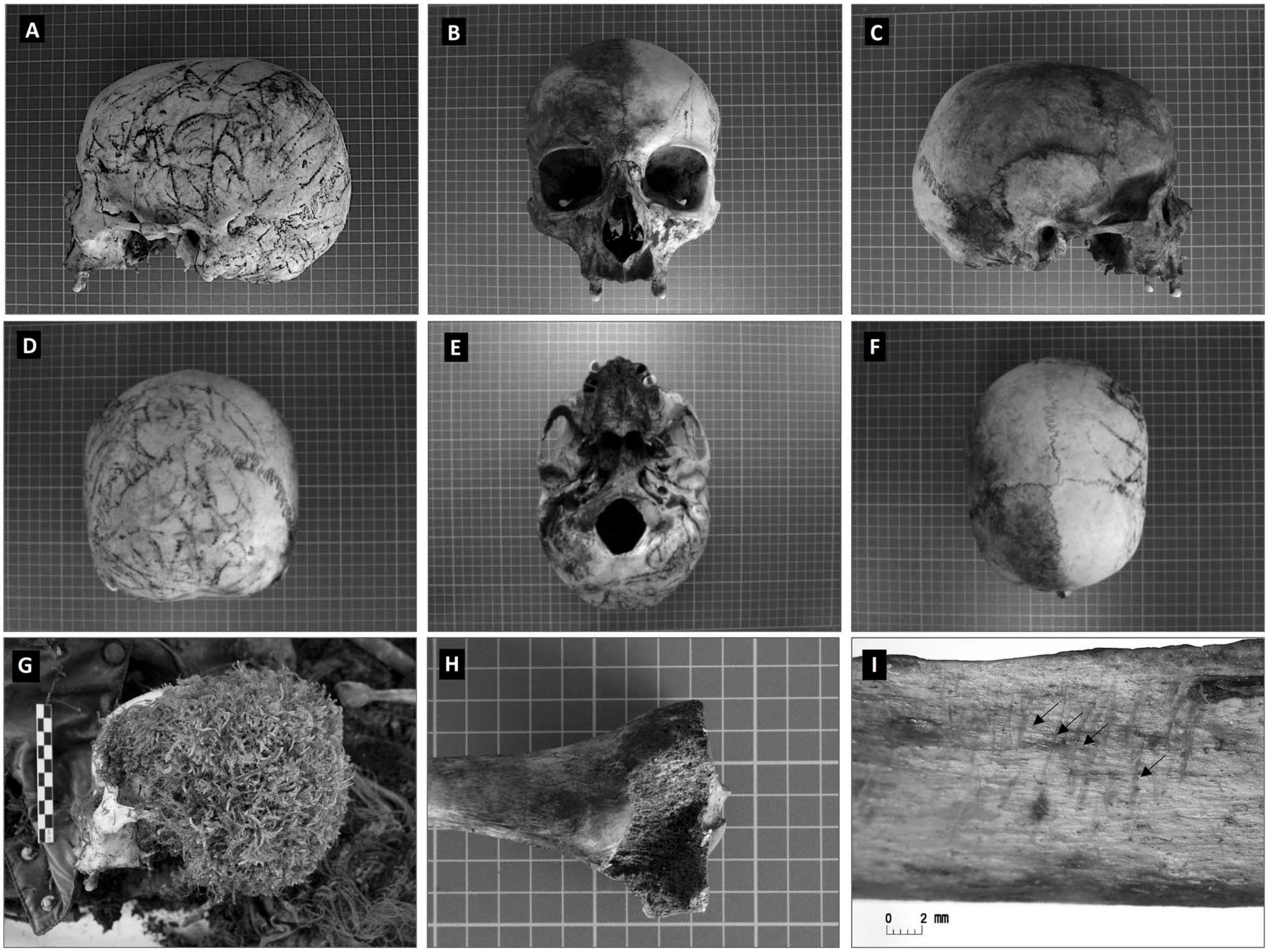

Figure 5 Skull discovered near Valenciennes (France). (A) Left lateral view showing root etching and staining. (B) Anterior view. (C) Right lateral view. (D) Posterior view. (E) Inferior view. (F) Superior view. (G) Left lateral view of the skull showing colonization by moss. (H) Taphonomic alterations, showing gnaw marks in the tibia. (I) Taphonomic alterations, showing gnaw marks in the rib.

As expected, the measured pMC exceeded 100% for all samples (Table 3, Figure 6), confirming their modern origin, and the different biological tissues yielded varying dates, reflecting the different time frames represented by each sample.

The teeth samples yielded calibrated dates of 1970–1972 (95.4% probability) for the lower canine and 1972–1974 (84.4% probability) or 1962–1963 (11.1% probability) for the upper canine. In contrast to bone tissue, there is little-to-no remodeling of dentin [62], and none of enamel [63]. Therefore, radiocarbon analysis reflects the timing of the mineralization of the dental tissue. Both teeth analyzed were canines, of which three-quarters of the root length are mineralized at 10.5 years [64]. Therefore, the year of birth can be estimated as 1960–1964, based on the combination of the estimation obtained from the lower and upper canines.

The vertebral cancellous bone sample, selected following the recommendation of Ubelaker et al. [50, 51], suggested a year of death of 1998–2002 (84.6% probability) and 1957–1958 (10.9% probability). The hair sample provided the most recent calibrated dates of 2013–2018 (83.3% probability) and 1955–1956 (12.1% probability).

This sampling strategy, involving a set of different biological tissues characterized by different developmental stages and rates of remodeling, enabled the assessment of both endpoints of the individual's lifespan: the year of birth and the year of death. The interval between these two dates is consistent with the age at death estimated by cementochronology.

By combining the radiocarbon information from the three biological tissues, we proposed that the female individual was born between 1960 and 1964, based on the dental samples, and that the year of death ranged between 2013 and 2018 based on the hair sample, and between 2006 and 2010 considering the vertebral cancellous bone (note that the results were 1998–2002, but an estimated 8.0-year lag time was added, considering the findings of Ubelaker et al. [50].

Here, the information provided by radiocarbon analysis was crucial not only for establishing the medico-legal significance, but also for narrowing down the pool of candidates for identification and scientifically supporting the initial leads from law enforcement agents. Based on these results, further identification protocols were initiated and bone samples were collected for DNA extraction by the Forensic Police Department in Lille. DNA analysis successfully confirmed the identification, further supported by the radiocarbon dating results.

Discussion

In their recent review, Franceschetti et al. [29] delineated two overarching categories for the application of PMI estimation

Table 3. pMC and calibrated dates for the human samples from Valenciennes.

Sample	Nature	pMC (%)	Calibrated dates (2σ, 95.4% probability)
22-182A	Hair	102.27 ± 0.38	1955 CE–1956 CE (12.1%) 2013 CE–2018 CE (83.3%)
22-182B	Vertebral cancellous bone	109.24 ± 0.41	1957 CE–1958 CE (10.9%) 1998 CE–2002 CE (84.6%)
22-182C	Lower canine (#43)	149.12 ± 0.56	1970 CE–1972 CE (95.4%)
22-182D	Upper canine (#13)	143.66 ± 0.54	1962 CE–1963 CE (11.1%) 1972 CE–1974 CE (84.4%)

CE: common era. The numbers in brackets indicate the specific tooth, following the World Dental Federation notation. pMC: percent modern carbon.

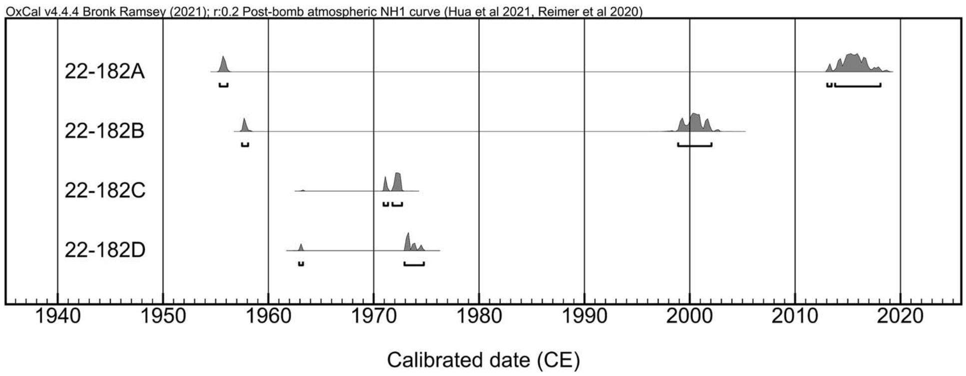

Figure 6 Calibrated dates for the samples from Valenciennes (France) using the Bomb21NH1 bomb-pulse calibration curve [43,47]. CE: common era.

methods: those aiming to determine the archaeological or forensic significance of human remains, and those aiming to refine the PMI once medico-legal significance is established. In their flow chart, radioisotope techniques such as ^{14}C analysis play a role in establishing the forensic interest; however, we argue that such analysis also serves a purpose in refining the PMI, and is a relevant approach for narrowing down the pool of candidates for identification purposes. Here, Case studies 1 and 2 demonstrate that radiocarbon dating indeed serves as a reliable initial step to establish medico-legal or archaeological significance. While Franceschetti et al. [29] do not include ^{14}C analysis in their list of methods to apply once forensic significance is known, the radiocarbon method can extend beyond expectations, as shown in Case study 3. This analysis was essential for scientifically supporting the initial leads from law enforcement agents regarding possible identification.

Case study 1 yielded a calibrated date range between 4332 and 4168 BCE, corresponding to the Neolithic period, and thus radiocarbon dating contributed to the preservation of original archaeological material. After the forensic investigation was officially endorsed by the legal authorities, the cranial remains were transferred to the archaeological authorities for curation. Neolithic occupations have been identified on the Channel and North Sea coasts of France [65]. According to the local archaeologists (*pers. comm.*), no prehistoric occupation has been identified at this specific location, but the remains were likely carried by littoral sea currents. Future steps are now the responsibility of archaeologists. The Ministry of Culture, leading the policy of safeguarding and protecting cultural heritage, has well-established procedures for inadvertent discoveries[5]. However, no legal provisions are delineated for archaeological human remains found in the context of a forensic investigation. Also, since forensic investigations are guided by the Ministry of Justice, the investigating magistrate can order the destruction of skeletal remains lacking medico-legal significance, in total contrast with the Heritage Code. Hence, interaction and significant crosstalk are required between the legal and archaeological obligations.

Case studies 2 and 3 illustrate the relevance of modern bomb-pulse dating and the importance of the lag time (the difference between the actual and estimated dates of death) in different biological tissues when discussing the medico-legal significance, and the importance of considering bone remodeling rates in the sampling strategy. The lag time is tissue-specific [51], age-related [50, 66], and possibly sex-specific [51], based on the timing of tissue modeling and the remodeling rate. These parameters must therefore be considered when sampling. Case study 2 yielded a radiocarbon date of 1974–1976 (81.3% probability), indicating a lack of medico-legal significance under the French judicial legal system 20-year statute of limitation. This date was estimated based on a femoral cortical bone, for which the lag time reaches a median of 29.5 years [51] and a mean of 32.0 years [67]. This brings the estimated year of death close to the 20-year statute of limitations. However, the biological profile showed that Case study 2 was a young adult (19.8–27.0 years), with fast tissue remodeling and ^{14}C values that can be considered close to atmospheric values [50]. A case involving an older individual and, consequently, a slower rate of bone remodeling would lead to the consideration of a longer lag time, prompting a reassessment of the medico-legal significance. This case highlights the importance of the recommendations established by Ubelaker et al. [50] to consider the age at death of the individual under study, and emphasizes the usefulness of this method, particularly in countries with longer or non-existent statutes of limitation for identification purposes.

Case study 3 yielded a year of birth falling within the range of 1960–1964, based on estimations from lower and upper canines of 1970–1972 (95.4% probability) and 1972–1974 (84.4% probability), respectively. The non-remodeling nature of dental tissues ensures the preservation of radiocarbon values from the time of their formation.

Using the published stages of tooth formation [64, 68], radiocarbon analysis allows the year of birth to be ascertained [49]. Dental enamel is the preferred tissue [30, 69] because of its precise and well-established developmental timeline. However, in this case, to ensure an adequate quantity of material for analysis, a sizable sample was taken and the analyses encompassed multiple biological tissues, resulting in wider lag times and reduced accuracy of the estimations. To sample only one tissue, such as enamel or primary dentin, at a precise location within the tooth root, would be necessary to refine the precision of the birth year estimate. Despite these constraints, the estimated year range overlaps the actual date of birth, demonstrating that tooth growth can reliably provide accurate chronological assessments.

Case study 3 also demonstrates that, when analyzing the radiocarbon bomb pulse, it is imperative to account for the lag time, which varies depending on the biological tissue being examined. The well-preserved remains in this case allowed hair to be sampled for analysis, and the completeness of the skeletal remains enabled us to select the vertebral cancellous bone for dating. Hair analysis provides information closer to the date of death [34, 70, 71], and bone turnover within the trabecular bone, particularly associated with hematopoietic marrow, is a suitable source for obtaining accurate chronological data [30, 51, 69]. The ranges for the year of death based on the hair and vertebral cancellous bone were 2013–2018 (83.3% probability) and 1998–2002 (84.6% probability), respectively. Despite the caution used when sampling the biological tissues, the two intervals do not overlap. The individual's disappearance was reported in mid-2012, but the actual date of death remains unknown. Consequently, the range estimated based on the bone sample might be presumed to overestimate the PMI by 10 years, while the second range, derived from the hair sample, could potentially underestimate it by 1 year. This 1-year lag unquestionably falls within the acceptable range. We speculated whether environmental factors, such as pollution or hair dye, could have influenced this outcome. However, a recent study showed that the application of hair dye does not significantly impact the ^{14}C concentration within samples [72]. The 10-year lag calculated from the vertebral cancellous bone closely aligns with the value reported by Ubelaker et al. [50], which was the lowest average lag value (8 years) observed across all bone types tested.

These case studies demonstrate that, despite potential challenges, radiocarbon dating can yield reliable PMI estimations, and is therefore a crucial tool in the initial stages of identification. The factors restraining the adoption of radiocarbon dating often include the cost and the implementation time, often overestimated by forensic practitioners [73]. Radiocarbon dating is reasonable in terms of time and cost compared with toxicological and genetic analyses. The costs for a single sample preparation and AMS dating services may range between $350 and $650. Practically, DNA analysis typically takes several months for standard cases, whereas radiocarbon dating using AMS can yield results in 2 weeks for standard processing, or within 1 week with priority processing. This allows a precise PMI estimation to be integrated into the further analysis strategy for identification.

Future research should prioritize investigations to quantify variations across different biological tissues, age groups, and sexes. Furthermore, it is imperative to assess the limitations of bomb-pulse dating for post-2010 forensic cases. This requires controlled investigations to evaluate the accuracy of radiocarbon dating for estimating the PMI in cases occurring within a short timeframe. Since the 2020s, the air radiocarbon concentration has returned to pre-bomb levels [47], resulting in modern samples with pMC values lower than 100%. Looking ahead, this decrease is expected to persist because of ongoing global emissions of radiocarbon-depleted fossil fuels [74]. To provide reliable data and to help distinguish between ancient and future radiocarbon sources, additional analyses such as sequential sampling [47] or stable isotope analysis [74] will be essential.

Conclusion

The case studies herein demonstrate the valuable insights that both traditional radiocarbon and bomb-pulse dating can provide for establishing the archaeological or medico-legal significance of human skeletal remains. This is paramount in areas of high archaeological potential, when contextual information may be lacking. Legal procedures cease once the archaeological relevance is established, saving both forensic practitioners and legal authorities valuable time and resources. Conversely, if medico-legal significance is established, radiocarbon assessments can help to narrow the pool of candidates for identification and to decide the best strategy for the identification process.

A sampling strategy involving different biological tissues, with varying developmental stages and remodeling rates, enables estimation of both the year of birth and the year of death, representing a valuable first step toward identification.

Radiocarbon dating has been firmly established for 70 years and complies with the principles of non-subjectivity, reliability, standardization, and reproducibility required in forensic sciences [75]. In addition to fulfilling crucial requirements of the judicial system, it provides benefits to both forensic scientists and archaeologists, and should be regularly incorporated into forensic investigation protocols.

Notes

1. French Penal code-Art 133-2, modified by law n°2017-242 (27th Feb. 2017-art. 2).
2. French Penal code-Art 74.
3. French Heritage code-Article L531-14.
4. https://www.culture.gouv.fr/Regions/DRAC-Hauts-de-France/Politique-et-actions-desservices/Pole-patrimoines-etarchitecture/Service-regional-del-archeologie-SRA-des-Hautsde-France/La-cartearcheologique
5. French Heritage Code-Art L531-14.

Acknowledgements

The authors would like to thank Frédéric Fèvre, General Prosecutor, Court of Appeal of Douai, France; Philippe Hannois and Jean-Luc Collart, Regional Curators, Regional Service of Archaeology, Directorate of Cultural Affairs of Hauts-de-France.

Authors' contributions

Benoit Bertrand conceived and designed this study. Carina Marques participated in the design. Benoit Bertrand, Valery Hédouin, Philippe Morbidelli, and Anne Bécart contributed to the forensic anthropology and odontology analysis and interpretation. Benoit Bertrand collected the samples. Thibault

Clauzel and Pascale Richardin performed pretreatment procedures and helped to conduct the interpretation of results. Benoit Bertrand, Carina Marques, and Thibault Clauzel wrote the manuscript. Benoit Bertrand, Carina Marques and Thibault Clauzel revised the manuscript. All authors contributed to the final text and approved it.

Compliance with ethical standards

In adherence to ethical principles, this investigation of the forensic cases strictly upholds confidentiality, respects the dignity of all individuals, and prioritizes the pursuit of truth and justice through rigorous methodology.

Disclosure statement

The authors declare that they have no conflicts of interest.

Funding

This work was supported with funding from the Hauts-de-France Region (France) (Dispositif STIMulE—Volet Partenarial STIP).

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