Radiocarbon Bomb Pulse Dating: A Guide for Forensic Casework

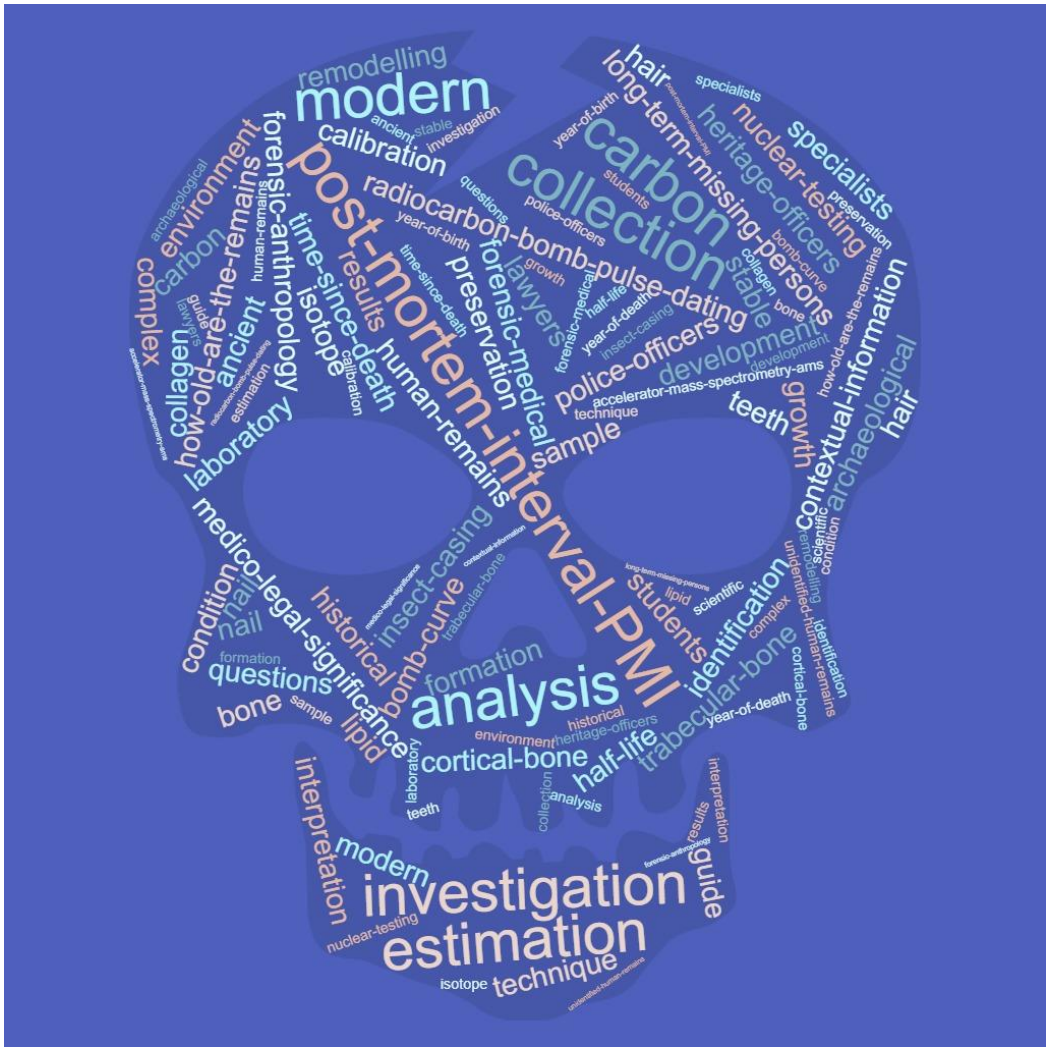

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Table of Contents

1. Introduction

A range of forensic medical and scientific specialists, as well as police officers, lawyers, heritage officers, and sometimes students, may be directly or indirectly involved in the analysis and investigation of unidentified human remains. Depending on the relative preservation of the remains and the availability of contextual information, one of the first questions that typically requires addressing is "how old are the remains?" Answering this question, that is, estimating the post-mortem interval (PMI) (also referred to as "the time since death") is notoriously difficult in cases of differentially preserved remains. One useful technique for potentially answering this question is radiocarbon bomb pulse dating. In addition to potentially assisting in determining whether the human remains are from the modern (as opposed to historic) era, bomb pulse dating may also be able to provide details about the year of death and/or birth of the individual. This information may assist the identification process by helping narrow the list of long-term missing persons for comparison to individuals reported missing around the time of the year of death.

This Guide was produced with the aim of providing a "user-friendly" resource to improve understanding and increase awareness of what bomb pulse dating is and the processes that are required for applying this technique.

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2. What is radiocarbon dating vs radiocarbon bomb pulse dating?

Radiocarbon is a naturally occurring, unstable isotope[1] of carbon, which is absorbed by all living organisms. After death the ^{14}C begins radioactive decay[2] (Hua et al., 2021). *Radiocarbon dating*, also known as carbon-14 (^{14}C) dating, is a technique that measures the amount (proportion) of radiocarbon (or ^{14}C) within materials such as wood, leather, paper, peat, shell, ivory, bone and teeth (Johnstone-Belford & Blau 2020). The rate at which ^{14}C decays is known and recorded, and therefore forms the basis for ^{14}C dating. Radiocarbon dating has traditionally been used to date archaeological remains that are of some antiquity, that is from 300 years of age to as old as 50,000 years before present (BP) (Taylor 1987). Typically, organic items are the focus of such dating but inorganic carbonate minerals such as limestone, dolomite or calcite can also be dated (see also Hajdas et al. 2021 for a comprehensive review). Radiocarbon dating of archaeological material involves a comparison of the level of ^{14}C decay within the sample, to the known half-life[3] of ^{14}C, which is 5730 ± 40 years (Goodwin 1962).

Radiocarbon dating can also be applied to cases of human remains that are admitted to forensic medical facilities, but it is not immediately obvious whether the remains are recent or not, and thus, if they are of medico-legal significance. Traditional ^{14}C dating can be used to interpret the results when they indicate the remains are older than 300 years old (Buchholz et al. 2018). However, if the results are shown to be modern (> 1950), then radiocarbon bomb pulse dating can be used to further interpret the results. Traditional ^{14}C dating is not applicable to recent forensic samples because samples that are less than 300 years old have not had time for the decay of ^{14}C to have an effect.

The application of ^{14}C dating to modern material (including human remains), known as *radiocarbon bomb pulse dating*, became possible due to anthropogenically produced radiocarbon resulting from worldwide above-ground testing of nuclear weapons that started in 1945 and intensified during the 1950-60s. This testing released high concentrations of artificial ^{14}C (sometimes referred to as "bomb carbon") into the atmosphere, almost doubling ^{14}C levels by 1963. Following the Nuclear Test Ban Treaty (1963), ^{14}C levels began declining. After ^{14}C is produced it is rapidly oxidized to carbon monoxide (CO) and then to carbon dioxide (CO_2). The levels of ^{14}C dropped due to dilution with fossil fuel CO_2 and

[1] Refer to the Glossary of Terms for an explanation of all technical terms.

[2] See Glossary of Terms.

[3] See Glossary of Terms.

incorporation in the biosphere (land oceans), and the subsequent absorption into plant life via photosynthesis[4]. This sudden increase and subsequent decrease in atmospheric ^{14}C concentrations have been plotted over the years from 1950 until 2021 in different areas in the northern and southern hemispheres (Hua et al., 2013; Turnball et al. 2017; Hua et al., 2021) to create what is known as a bomb pulse curve (Fig. 1). This curve is used to interpret the results of ^{14}C values measured in various samples of human tissues to attempt to date the remains. The bomb pulse curve used for analysis should include data from the closest geographical location to the remains. In bomb pulse dating the relative amount (fraction) of ^{14}C is the total amount of carbon. The fraction of ^{14}C is determined by how much atmospheric ^{14}C is already taken up by other carbon-containing materials (see below).

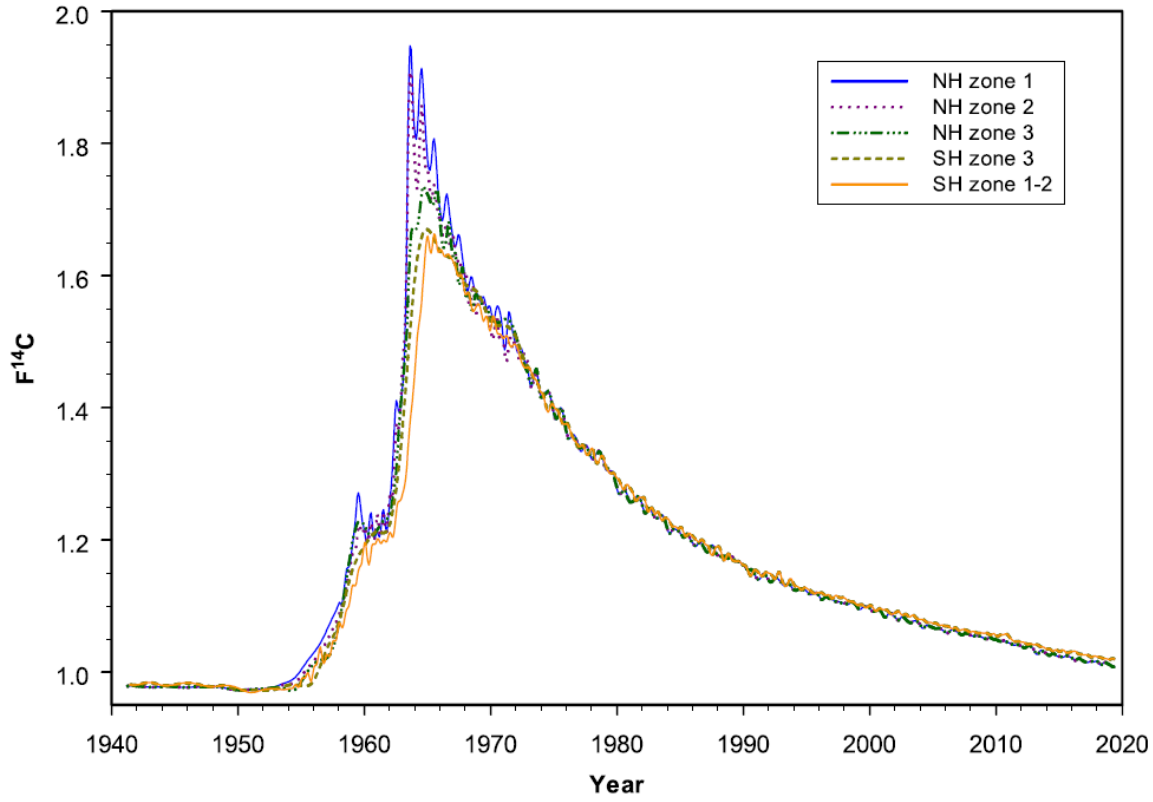

Fig. 1: Average ^{14}C from 1950-2020 for northern hemisphere (NH) and southern (SH) hemispheres (after Hua et al., 2021). NB: $F^{14}C$ (y-axis) indicates "fraction modern"[5].

[4] See Glossary of Terms.

[5] See Glossary of Terms.

3. How can bomb pulse dating help when human remains are located?

3.1. Determining whether the remains are of medico-legal significance

When human remains are discovered and are not immediately identifiable, understanding whether the remains are of medico-legal, as opposed to historical or archaeological significance[6], is an important part of the investigation and may assist in the identification process. However, depending on the context, determining whether differentially preserved human remains are ancient or modern may be problematic (Sutton & Byrd 2020). While a forensic anthropologist will visually examine and describe the condition of the skeletal remains and may attempt to estimate the PMI (Behrensmeyer 1978), correlating the effects of skeletal weathering with time is typically unreliable because of the complex nature of decomposition (Blau & Forbes 2016). Therefore, estimation of the PMI from a visual examination of the skeletal remains is limited and is often associated with wide estimation ranges (sometimes greater than 20 years) (Ross & Cunningham 2011). Bomb pulse dating may be used in such cases to provide more detailed information, specifically, to determine whether remains are from the modern era. As "modern" is defined as 1950[7], bomb pulse dating may be used to determine if the individual died before or after 1950 (Case Example 1).

3.2. Estimating the year of death and the year of birth

Remains that are determined to be of medico-legal significance, that is, an individual who died within the previous 100 years, may, depending on the tissues available for analysis, be further analysed to estimate their year of death (Case Example 2) and the year of birth (Case Example 3).

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[6] Most Australian State and Territory legislations do not specifically define a time period for when the remains are of medico-legal significance. Practitioners typically, therefore, make assumptions (which may be guided by the case investigator) that remains older than 100 years are of no medico-legal significance. The exception to this is the New South Wales (NSW) and Victorian (VIC) legislation which clearly defines a time period in which human remains are of medico-legal significance. NSW: a coroner does not have jurisdiction to investigate the death unless the death occurred within the last 100 years; or if the remains found have no connection with NSW - Section 13B & 13C, NSW Coroners Act, 1980. VIC: A coroner may investigate a death that is or may be a reportable death if the death appears to have occurred within 100 years before the death was reported to a coroner. A coroner must investigate the death if the death occurred within 50 years before the death was reported to the coroner (VIC Coroners ACT, 2008 (Part 4, Div 1, 14.1).

[7] 1950 is year 0 before present (BP) by convention in radiocarbon dating and is deemed to be the 'present' (modern). This is because wood dating to 1890 was chosen as the absolute radiocarbon standard as it was growing prior to the fossil fuel effects of the industrial revolution and the activity of 1890 wood is corrected for radioactive decay to 1950. The year 1950 was subsequently chosen to represent 'modern" to acknowledge the publication of the first radiocarbon dates calculated in December 1949 (Taylor 1987: 97).

Case Example 1: Establishing the medico-legal significance of human remains

In 2002 a disarticulated cranium and mandible were found encased in plastic in a riverbed in Pennsylvania, United States of America. As the remains were completely skeletonised, time since death was difficult to estimate. Consequently, ^{14}C dating was used to determine if the remains were of medico-legal relevance. A bone sample of approximately 5 cm from the cranial vault was analysed to determine the ^{14}C level within the bone. The results of the ^{14}C analysis showed the remains contained ^{14}C levels consistent with the pre-bomb pulse era (pre-1950), and therefore, the skull was deemed to be of no medico-legal significance (Ubelaker & Houck 2002).

Case Example 2: Establishing the year of death

Wild and colleagues (2000) assessed the accuracy of hair and bone samples to determine year of death in two cases where the individuals' dates of death were known. The analysis of the hair samples provided an estimated year of death within +/- 1 year for both individuals. The bone analysis, as expected, was less accurate (see below for an explanation) The estimated year of death for both individuals was between +/- 5-30 years. (See Handlos et al., 2018 for another example).

Case Example 3: Establishing the year of birth

In 2010, unidentified remains were discovered in an artificial lake in Northern Italy. While police had an identification hypothesis that the individual was a 36-year-old male born in 1973 who disappeared in 2009, this could not be confirmed from a visual examination of the remains. Multiple tissue samples, with different turnover rates, were collected and analysed using bomb pulse dating at the University of Salento, Italy, to estimate both the year of birth and the year of death. Overall, the analysis of two teeth provided an estimate of year of birth within 2-3 years of the suspected year of birth, while the hair contained 14C consistent with atmospheric 14C levels in 2009 (the estimated year of death) (Calcagnile et al., 2013). (See Speller et al., 2012 for another example).

Information about the year of death and/or birth may assist in focussing identification efforts by helping narrow the list of long-term missing persons for comparison to individuals reported missing around the time of the year of death.

4. Applying the bomb pulse dating technique

Bomb pulse dating is a multi-disciplinary analysis involving three main steps: sample collection, preparation and analysis, and interpretation.

4.1. Sample selection

As discussed above, every living organism absorbs and assimilates ^{14}C. However, different tissues in the human body develop and remodel at varying rates which influence the levels of ^{14}C. Compared to bone for example, hair and nail, are relatively short-lived tissues with a relatively fixed turnover rate. Consequently, the levels of ^{14}C in hair and nail reflect ^{14}C levels similar to the environment around the time of death. In contrast, bone has a relatively slow turnover affected by many variables including growth, mechanical loading and hormonal changes. The complex nature of bone turnover[8] throughout the lifetime of an individual means the interpretation of ^{14}C levels in bone is relatively more difficult (Wild et al., 2000). Depending on the question being asked (see above), and the relative preservation of remains, different sample types will be required (Johnstone-Belford et al., 2022) (Tables 1-3).

[8] See Glossary of Terms.

Table 1: Sample types for bomb pulse dating to address the medico-legal question: "*Are the remains from a historical person or someone who lived in the modern period (post-1950)?*"

Sample Type	Amount	Comment	Advantages	Limitations
Bone	c. 2 cm (500-3000 mg[9])	While approximately 2 cm is ideal, depending on preservation, as little as 500 mg (i.e. the amount when ground which is less than a teaspoon) may be sufficient for analysis. Both cortical and trabecular bone[10] should be collected for analysis if possible. Only a small sample of bone is needed, however it is essential that the sample includes trabecular bone in order to determine if the remains are from the modern era (Fig. 2). Recent research indicates vertebral bodies[11] provide the most reliable results for estimation of time-since-death as there is comparatively rapid bone turnover and therefore a lower radiocarbon lag time (Ubelaker et al., 2022).	Bone is usually one of last of the body's tissues to decompose/degrade.	Skeletal elements form at varying ages, and during life, different bones develop and remodel at different rates (e.g., the petrous portion of the temporal bone has low turnover compared to vertebrae which have a rapid bone turnover), with remodelling slowing with advancing age (Hedges, et al., 2007; Ubelaker et al., 2022). The complex nature of bone development, growth, and turnover (remodelling) means that bone as a tissue sample for ^{14}C dating only provides the last time of turnover, not the actual 'age' of the remains. If the person was elderly, it is likely there is a "lag time" between the ^{14}C value and the actual date of death (Ubelaker et al., 2022). This complexity means interpreting results may be difficult. Ideally, information about the specific bone used for the analysis and the turnover (remodelling) rate of that skeletal element, and the age at death of the individual should all be considered when interpreting results. In many cases, however, such details may not be available.

[9] Depending on preservation.

[10] See Glossary of Terms.

[11] Details of which vertebra (i.e., cervical, thoracic, or lumbar) are not provided in the publication. It should also be noted that bones such as ribs and iliac crest are also considered "active" bones.

Table 2: Sample types for bomb pulse dating to address the medico-legal question: "*What was the person's year of birth?*"

Sample Type	**Amount**	**Comment**	**Advantages**	**Limitations**
Tooth (dental enamel)	At least one tooth	Preferably a molar without dental or taphonomic alteration. Because there are well established rates of dental development (Schour & Massler 1940), this information can easily be compared to the ^{14}C results to determine which year the tooth formed. For example, if the analysis of ^{14}C in a sample from a 2nd permanent molar tooth indicated the dental enamel formed in 1960, because it is known that enamel for this tooth forms between 5 and 8 years of age (Scheuer, 2000), it is possible to estimate that the individual was born between 1952-1955. The analysis of multiple teeth can determine which estimated year of birth range (upside or downside of the curve) is correct.	Teeth do not remodel after enamel formation and therefore contain the ^{14}C content from the year of formation. Teeth typically survive both normal decomposition as well as artificial means of destruction such as fire or chemical treatments (Ritz-Timme et al., 2000). Previous studies have found teeth to provide highly accurate estimations of the year of birth for individuals born post-1950, with estimations usually between 1-2 years of actual birth (Baustian et al., 2014; Wang et al., 2016).	The availability of samples will depend on the preservation of the head, and/or oral health of the person.

Table 3: Sample types for bomb pulse dating to address the medico-legal question: "*What was the person's year of death?*"

Sample Type	Amount	Comment	Advantages	Limitations
Bone (Lipids[12] found in trabecular and cortical bone)	Approx. 5 g	As little as 500 mg of bone is required for the analysis of bone collagen (see above), however, a greater amount (5 gm) of bone is required for the analysis of bone lipids. If the remains are shown to be from the modern era, the selection of another bone sample will allow placement on the curve to comment of the date of death (Ubelaker et al., 2022).	Bone is usually one of the last of the body's tissues to decompose/degrade.	There is more rapid carbon turnover in bone lipids compared to bone collagen, however, lipids do not always survive in the environment (Handlos et al., 2018; Wild et al., 1997; Wild et al., 2000). Neither lipids nor trabecular bone provide a precise date. While other tissues (blood, skin, etc) can be used, bone may be all that survives. The effects of mummification on 14C are unknown.
Tooth (Dental enamel and/or dentine)	At least one tooth	Preferably a molar without dental or taphonomic alteration. While the analysis of dental enamel does not specifically provide the year of death, analysis of both tooth enamel and dentine (tooth root) can help determine which side of the curve is correct for the year of death estimation. Two dates are needed to determine which side of the curve should be used. The dentine may have a long turnover, but in this case, what is needed are measurements of an early formed and later formed tissue to determine the side of the curve.	Teeth do not remodel after enamel formation and therefore contain the ^{14}C content from the year of formation. Teeth typically survive both normal decomposition as well as artificial means of destruction such as fire or chemical treatments (Ritz-Timme et al., 2000).	Availability of samples will depend on the preservation of the head, and/or oral health of the person.

[12] See Glossary of Terms.

Table 3…..cont.

Sample Type	Amount	Comment	Advantages	Limitations
Hair	Approx. 10 strands	Approx. 3- 4 cm long samples of head hair should be taken as close to the scalp as possible, however, the roots are not necessary. If the head hair is very short, more than 10 strands should be collected. Other body hair (e.g., pubic, arm, etc) can also be used.	Hair is known to have a fast growth rate, on average, 1 cm per month (Kintz 2017) and therefore will reflect ^{14}C levels similar to the environment around the time of death. Sampling hair is relatively non-destructive. Unlike most soft tissues, hair is known to survive decomposition (Geyh 2001) and can even be found on archaeological remains (Petraru et al., 2020).	Hair dyes can cause contamination to radiocarbon measurements (Santos et al., 2015). The availability of samples will depend on preservation.
Nail	An entire fingernail or toenail	An entire nail is preferable because the section nearest the nail bed will contain the most recent ^{14}C.	Nails are fast-growing, around 3 mm per month (Solimini et al., 2017), and therefore will reflect ^{14}C levels similar to the environment around the time of death. Sampling nail is relatively non-destructive. As with hair, nails are known to survive decomposition due to their high keratin content (Inkret et al., 2020). Hair and nails have been shown to provide accurate estimates of the year of death, typically between 1-3 years of actual death (Nakamura et al., 2007; Wild et al., 2000).	The availability of samples will depend on preservation. The effects of long-term nail treatments (e.g. polish) may affect the analysis and are currently being investigated (Johnstone-Belford et al. in prep).
Puparia (the hardened casing of insects)	3-4 cases	As fly larvae feed solely on decomposing flesh, their discarded casings will often reflect ^{14}C levels consistent with environmental radiocarbon around the time of death.	Puparia are often found in association with decomposed human remains and may, therefore, be useful when other tissue types are not present (e.g., due to decomposition).	Availability of samples will depend on the preservation of the remains which will be influenced by many variables, including the deposition context (e.g., burial may inhibit the presence of insects).

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Fig. 2: Cross section of a human femur sample from which bone powder was collected for analysis. White arrow (oval defect) indicates the area of collection (Image: authors).

4.2. Sample collection

The number and type of samples collected will be dictated by both the condition and preservation of the remains, and the relevant questions (see Tables 1-3). In cases where there is little or no contextual information it is likely that the medico-legal significance and the identification of the person will both be in question. Ideally, therefore, at least two bone samples (one trabecular and one cortical bone), one tooth and either hair or nail should be collected. Sample collection can occur either at the scene (in the case of hair, nail, or puparia), or in the mortuary during the post-mortem examination.

4.3. Sample preparation and analysis

Samples should be packaged in clearly labelled and secure sample bags. The type of bag does not matter, as long as the sample is secure and dry. Plastic bags may be more secure for small samples such as hair or nail. The bagged samples will then need to be couriered to a radiocarbon dating laboratory (detailed below) for processing and analysis. Once received at the dating laboratory, the sample/s will undergo chemical pre-treatment to extract the carbon from the sample, followed by analysis using accelerator mass spectrometry (AMS)[13] (Fig. 3) to determine the concentration of ^{14}C within the sample. For more information regarding sample preparation and analysis please visit https://www.ansto.gov.au/our-facilities/centre-for-accelerator-science/radiocarbon-dating or https://earthsciences.anu.edu.au/anu-radiocarbon-laboratory.

[13] See Glossary of Terms.

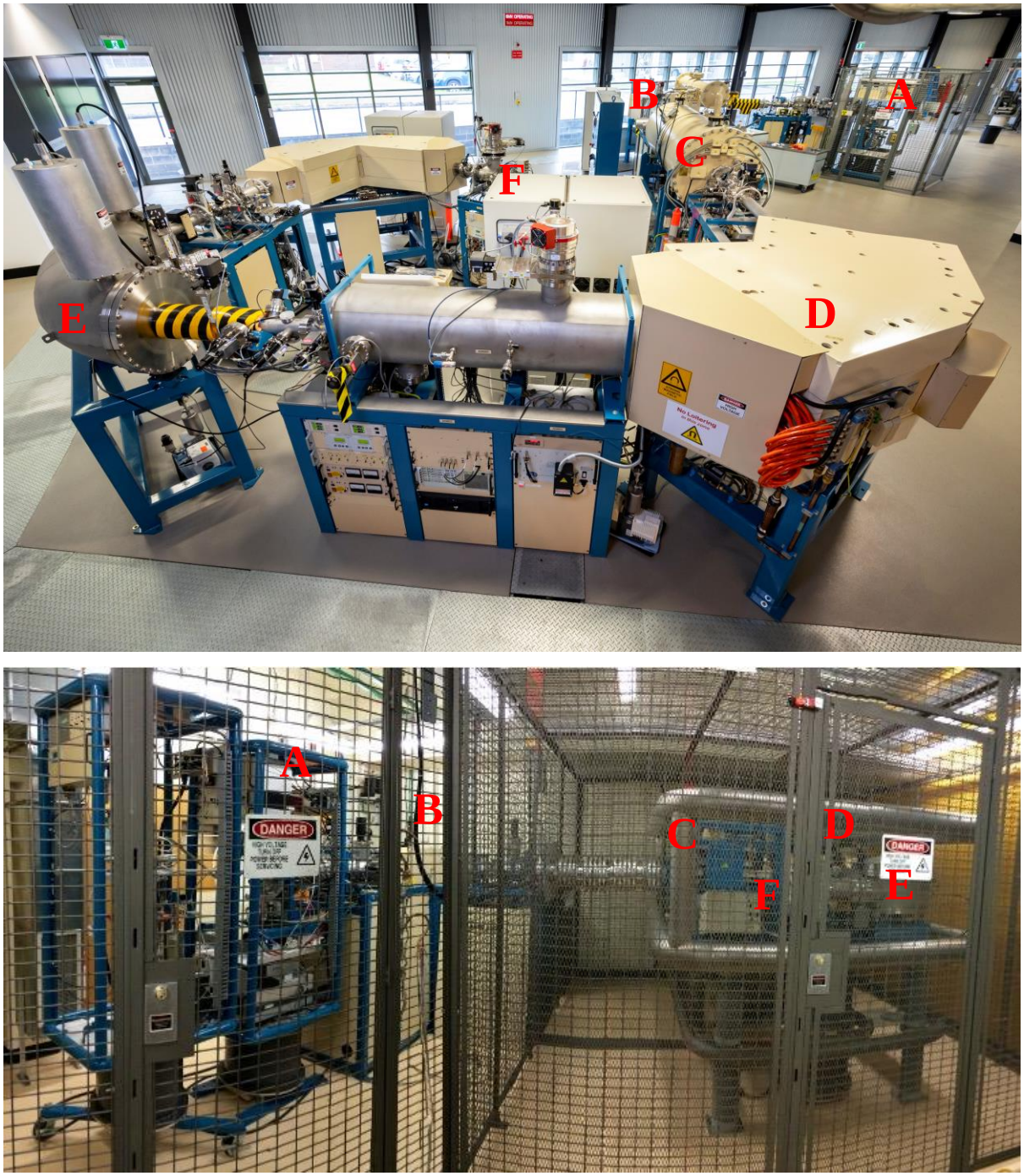


Fig. 3: Different views of two accelerator mass spectrometers (AMS). Top (ANSTO): A = the ion source; B = the injector magnet; C = the tandem accelerator; D = the analysing magnet; E = the electrostatic analyser; F = the gas ionization detector (Image: ANSTO); Bottom (single stage accelerator mass spectrometer at ANU). A = the iron source; B = the injector magnet; C = the high voltage deck accelerator; D = the analysing and switching magnet; E = the electrostatic analyser; F = the silicon barrier detector (Image: ANU).

4.4. Sending samples to a dating laboratory

If samples are being sent to a laboratory in Australia, they can be sent through Australia Post via registered or courier mail. If the samples are going overseas it is recommended they be sent by courier. In such cases, it will be necessary to complete a custom import permit form. It is also important to check whether the receiving country has specific regulations for receiving biological (human) samples.

4.5. Interpreting results

Results provided by the dating laboratory are typically presented in a table, often with an accompanying graph. The concentration of ^{14}C is described in terms of the "fraction modern" ^{14}C ($F^{14}C$) with an associated error rate or, presented as a ^{14}C calibrated age. The calibrated age will either be given as a specified year range (e.g., 1564-1655) if the sample is pre-bomb pulse, or reported as ">modern" meaning the sample age is post-1950 (Table 4).

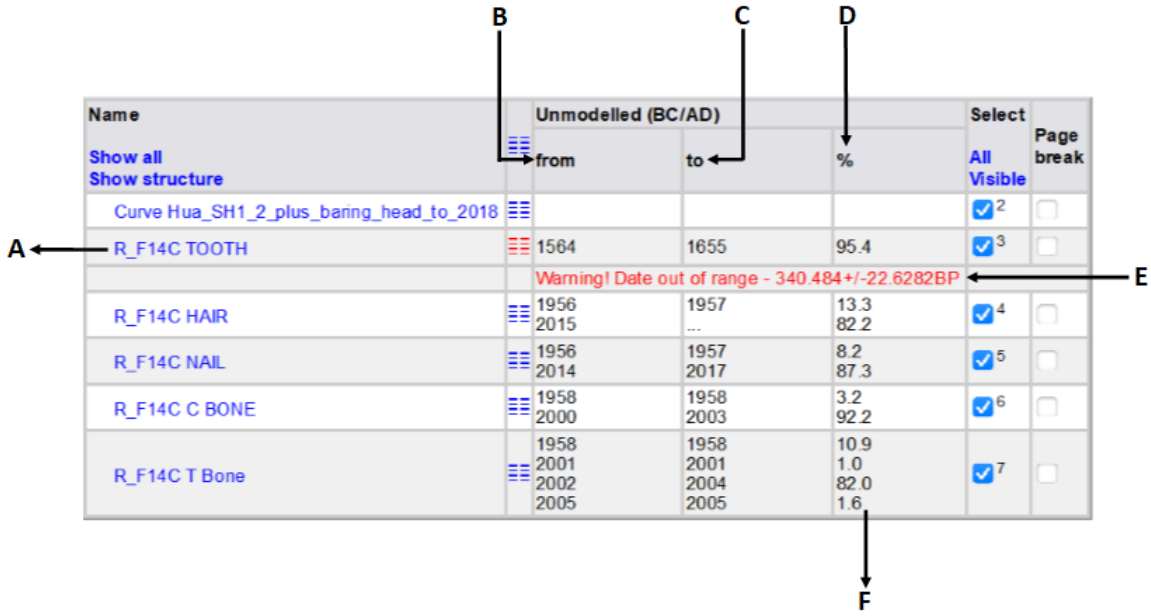
Table 4: An example of radiocarbon results.

Lab Code	Sample type	Sample ID	$F^{14}C$	±	^{14}C Calibrated Age
9127	Tooth	001. tooth enamel	0.9585	0.0027	1564-1655 AD*****
9135	Hair	002. hair	1.0267	0.0020	>MODERN******
9288	Nail	003. nail	1.0288	0.0018	>MODERN
9298	Bone	004. cortical bone	1.0869	0.0025	>MODERN
9300	Bone	005. trabecular bone	1.0818	0.0025	>MODERN

***** Calibrated age

******Radiocarbon (^{14}C) age: ">MODERN" means the age is >1950

While these results provide information regarding the forensic relevance of the remains, further interpretation is needed to estimate the year of death and/or the year of birth. This involves the comparison of the fraction (F) ^{14}C in the sample, to a geographically relevant (i.e., southern or northern hemisphere) bomb pulse curve to determine what year the tissue in question was formed. This is typically achieved with the use of free online software, such as OxCal (https://c14.arch.ox.ac.uk/oxcal.html) or CaliBomb (http://calib.org/CALIBomb/). These programs analyse $F^{14}C$ results and compare them to known atmospheric levels of ^{14}C from both the southern and northern hemispheres. The programs then provide a calibrated year range (often multiple ranges) for tissue formation. The results can be presented both in table (Fig. 4) and graph (Fig. 5) formats. While in most cases, a graph will provide a clearer and more understandable overview of the radiocarbon results, the table will provide precise year range estimates for the year of tissue formation.



KEY

A: Samples (often teeth) that developed before 1950 cannot be accurately dated using either bomb pulse dating or radiocarbon dating. These results should only be utilised to determine that the sample originated before 1950.

B: This range represents the lower year in the predicted range.

C: This range represents the higher year in the predicted range.

D: This percentage is the probability level for the highest probability density range, i.e., the likelihood that the correct value is in that range.

E: A warning may indicate that the sample formation extends further than the beginning (1950) or the end of the bomb pulse curve (which is 2018 in this case) and may decrease accuracy.

F: It is common that multiple year ranges will be calibrated for each sample, each with a different accuracy percentage. Usually, these predicted ranges include one range on the upside of the bomb pulse curve (pre-1963) and one on the downside (post-1963). There may, however, be multiple ranges on either side of the curve. These ranges correspond to multiple instances of environmental radiocarbon levels that match the level found within the sample All age ranges are valid. Typically, the most accurate range (i.e. the value with the highest percentage) should be used.

Fig. 4: An example of an OxCal output table for calibration of $F^{14}C$.

When the results include multiple ranges, they may be presented in a table as a list (see Fig. 4) or expressed as multiple peaks when displayed graphically (Fig. 5). Typically, there are two possible calibrated year ranges, one on the upside, and one on the downside of the bomb curve. This occurs because the ^{14}C fraction within the sample will usually correspond to atmospheric ^{14}C levels on both the upside and the downside of the curve, as environmental levels increased and subsequently decreased. If both trabecular and cortical bone have been analysed, the correct side can easily be determined because of differences in turnover in these two bone types (see Table 1). If the trabecular bone has a higher level of ^{14}C than the cortical bone, the remains belong on the upside of the curve, while the opposite is true if the cortical bone has higher levels of ^{14}C.

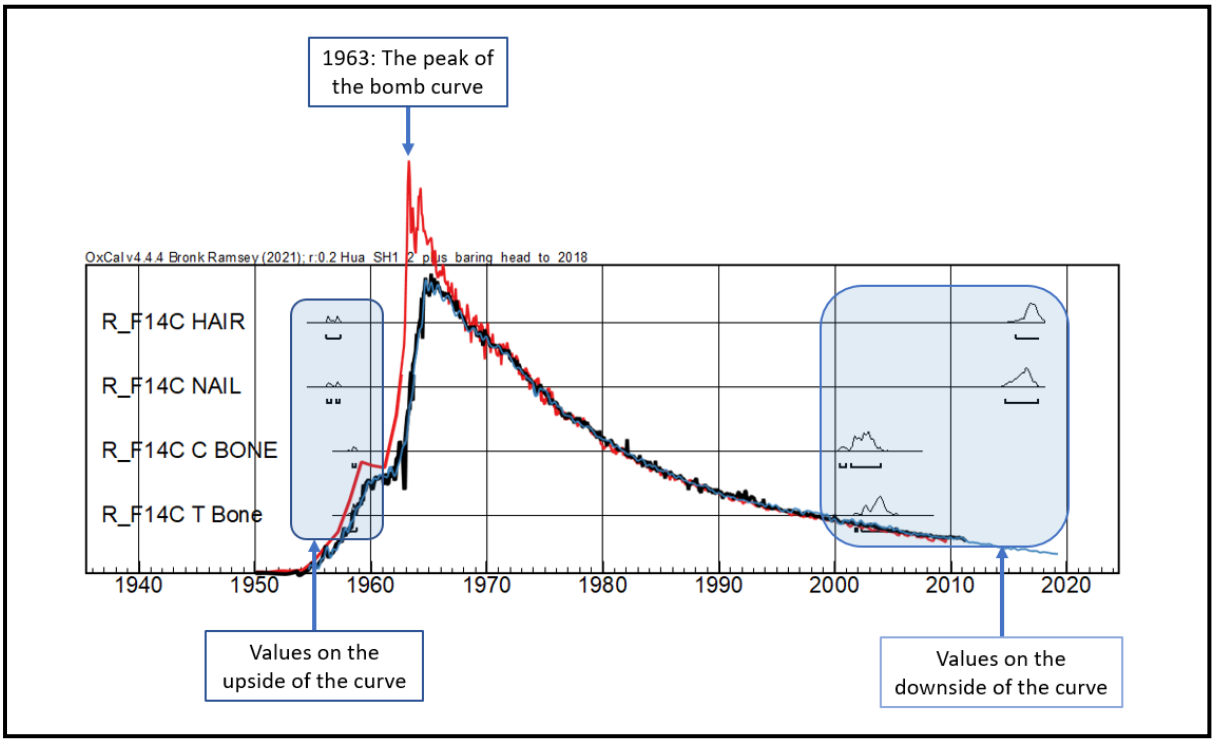


Fig. 5: Graphical representation of post-1950 samples

The calibrated year range can be directly used to estimate year of death, as hair and nail are fast growing tissues which contain levels of ^{14}C consistent with the year of death. However, the year of birth can be estimated if the tooth enamel formation has occurred after 1950 (post bomb pulse). If the formation occurred before this time, the year of birth can only be determined as pre-bomb pulse, that is, before 1950. In teeth that have formed post 1950, the calibrated tooth enamel formation year range must be extrapolated and compared to anthropological tooth formation standards to estimate the year of birth.

Although ^{14}C content is a direct measurement, the potential impact of dietary offsets and bone protein turnover (i.e. remodelling) needs to be considered (Hedges et al., 2007) when interpreting results. Consequently, the dating of human bone can have up to a +/-20-year error.

5. Where can samples be processed for bomb pulse dating?

Bomb pulse dating involves the analysis of samples via accelerator mass spectroscopy (AMS). This is highly specialised technology, and as such can only be performed at specific facilities. Within Australia there are two radiocarbon dating laboratories:

- The Australian Nuclear Science and Technology Organisation (ANSTO) https://www.ansto.gov.au/our-facilities/centre-for-accelerator-science/radiocarbon-dating.
- Australian National University (ANU) Radiocarbon Dating Laboratory https://earthsciences.anu.edu.au/anu-radiocarbon-laboratory.

There are numerous AMS facilities outside Australia including (but not limited to):

- Beta Analytic Testing Laboratory (Florida, USA) https://www.radiocarbon.com/carbon-dating-bones.htm
- Radiocarbon Dating Laboratory- The University of Waikato (New Zealand) https://radiocarbondating.com/.
- Rafter Radiocarbon Laboratory at Geological and Nuclear Sciences (GNS) (New Zealand) https://www.gns.cri.nz/Home/Services/Laboratories-Facilities/Rafter-Radiocarbon-Laboratory.
- Scottish Universities Environmental Research Centre (SUERC) Radiocarbon dating laboratory (Glasgow, Scotland) https://www.gla.ac.uk/research/az/suerc/c14/.

6. How much does bomb pulse dating cost?

The cost of bomb pulse dating varies between laboratories, and for different sample types. Hair and nail require less preparation and chemical treatment, and so are generally more affordable to analyse than bone, which requires a more complex pre-treatment. As such, within Australia, costs may vary between $300-800 per sample.

The cost generally includes the calibration (i.e. conversion) of the ^{14}C content into a calendar age. In addition, an assessment of the likely age of death given bone protein turnover rates (for cortical bone this approximates 10-20 years depending on the age of the individual) and dietary offsets (which are often regional dependent) is provided. The cost also includes stable isotope analysis of ^{13}C and ^{15}N. These analyses are used to estimate the amount of marine foods in the diet of the individual which have the greatest potential to cause significant reservoir offset[14].

7. How long does it take to receive results?

Radiocarbon results will typically be returned within 3-6 months, depending on the laboratory used, and the urgency of the results.

[14] See Glossary of Terms.

8. Glossary of Terms

A

Accelerator mass spectrometry (AMS): An ultra-sensitive analytical technique which uses a particle accelerator to count the relative number of atoms of different carbon isotopes present in the material (e.g., bone, teeth, hair, nail, etc).

Atom: The smallest unit of matter that contains protons, neutrons and electrons.

Atomic mass: Average mass of the atoms of an element (e.g., Carbon has 6 protons and 6 neutrons and is written ^{12}C to reflect its atomic mass).

B

Bone turnover: Process of reabsorption of old bone, and consequent replacement of new bone. Bone turnover occurs throughout an individual's life with little to no change in the bone morphology.

C

Calibrated: the process of converting a radiocarbon age into a calendar age. Typically, this is undertaken using free online software, such as OxCal (https://c14.arch.ox.ac.uk/oxcal.html) or CaliBomb (http://calib.org/CALIBomb/).

Cortical bone: Dense outer surface of a bone that makes up nearly 80% of skeletal mass.

E

Element: A substance that cannot be separated into simpler substances by ordinary chemical processes. Examples of elements include carbon and hydrogen.

F

Fraction modern ($F^{14}C$): also known as "percentage modern carbon" (pMC), is a measurement of the deviation of the $^{14}C/^{12}C$ ratio of a sample from "modern" (i.e. 1950) and is the term used to describe post-bomb samples.

H

Half-life: The time taken for the radioactivity of a specified isotope to fall to half of its original value. For each isotope the half-life is constant and unaffected by changes in the environment. The constant nature of half-lives means radioactivity can be used as a "clock" to measure elapsed time, provided that the original quantity of the isotope present is known. The half-life of ^{14}C is 5730± 40 years

I

Isotope: Two or more types of atoms of a chemical element that have the same atomic number and position in the periodic table. They have nearly identical chemical behaviour but have different atomic masses and physical properties. E.g., ^{12}C, ^{13}C and ^{14}C are all isotopes of carbon.

L

Lipids: Are fatty, waxy, or oily compounds that are soluble in organic solvents and insoluble in solvents such as water. Lipids are found in trabecular and cortical bone and depending on preservation, can be extracted for ^{14}C dating.

M

Mass spectrometer: An analytical tool useful for measuring the mass-to-charge ratio of one or more molecules or ions present in a sample. A mass spectrometer is used to measure the isotopic ratio in carbon.

P

Photosynthesis: The process by which plants use sunlight, water, and carbon dioxide to create oxygen and energy in the form of sugar.

R

Radioactive decay: The process by which an unstable atomic nucleus loses energy by radiation.

Reservoir offset: The presence of old carbon within a carbon reservoir that is incorporated into the living organism, e.g. ocean, food, etc.

S

Stable isotopes: Non-radioactive forms of atoms; they do not decay into other elements vs. unstable isotopes which will decay into other elements.

T

Trabecular bone: Porous, spongy bone typically found at the core of vertebral bones, or at the ends of long bones.

9. References

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