Forensic Radiocarbon Dating of Human Remains: The past, the present, and the future

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Abstract

Radiocarbon dating is a valuable tool for the forensic examination of human remains in answering questions as to whether the remains are of forensic or medico-legal interest or archaeological in date. The technique is also potentially capable of providing the year of birth and/or death of an individual. Atmospheric radiocarbon levels are currently enhanced relative to the natural level due to the release of large quantities of radiocarbon (^{14}C) during the atmospheric nuclear weapons testing of the 1950s and 60s. This spike, or 'bomb-pulse', can, in some instances, provide precision dates to within 1-2 calendar years. However, atmospheric ^{14}C activity has been declining since the end of atmospheric weapons testing in 1963 and is likely to drop below the natural level by the mid-21st century, with implications for the application of radiocarbon dating to forensic specimens.

Keywords: radiocarbon, dating, human remains, forensic science, forensic anthropology

1. Introduction

Radiocarbon dating is most routinely applied to archaeological and environmental studies, but in some instances can be a very powerful tool for forensic specimens. Radiocarbon (^{14}C) is produced naturally in the upper atmosphere by the interaction of cosmic rays on nitrogen-14 (^{14}N). The ^{14}C produced is rapidly oxidised to carbon dioxide, which then either enters the

terrestrial biosphere via photosynthesis and proceeds along the food chain via herbivores and omnivores, and subsequently carnivores, or exchanges into marine reservoirs where it again enters the food chain by photosynthesis.

Natural production levels of radiocarbon vary very little, and over thousands of years the rate of production of ^{14}C has been approximately equal to that of the rate of take up. All living organisms are constantly taking up and assimilating ^{14}C, and their tissues are in approximate equilibrium with current atmospheric radiocarbon levels. Once they die, however, organisms stop taking up radiocarbon, and its natural decay, with a half-life of ~ 5730 years, allows archaeological and environmental samples to be dated by measuring the ratio of $^{14}C/C$ as far back as ca. 50,000 years ago.

However, with the start of the Industrial Revolution in the 18th century and the associated burning of fossil fuels, large amounts of carbon dioxide were released into the atmosphere that were devoid of radiocarbon, effectively diluting the atmospheric ratio of $^{14}CO_2/\ ^{13}CO_2/\ ^{12}CO_2$. Known as the Suess Effect (Suess 1953, 1955), this has resulted in a 300-year period, from approximately 1650 to 1950 AD, within which it is almost impossible to distinguish between dates using radiocarbon.

Natural atmospheric levels were subsequently further altered by the release of vast amounts of radiocarbon by atmospheric nuclear weapons testing in the northern hemisphere during the 1950s and early 1960s. This spike in radiocarbon activity peaked in 1963 when the USA, the UK and the USSR stopped testing, having signed the Partial Nuclear Test Ban Treaty that autumn. At this point, atmospheric ^{14}C activity was nearly double that of pre-industrial times in the northern hemisphere, and had increased by approx. 65% in the southern hemisphere (Cook and MacKenzie, 2014). Since 1963, radiocarbon levels have declined steadily and are presently still above pre-1950s levels. This decrease is due to atmospheric mixing and exchange with the terrestrial and marine carbon reservoirs, rather than radioactive decay. The decline was also assisted by the end of all atmospheric nuclear testing in 1980 (specifically by France and China). Although all atmospheric nuclear weapons tests were undertaken in the northern hemisphere, global variation in atmospheric radiocarbon activity is now minimal due to wind currents and related factors (Ubelaker et al 2015).

This rapid increase in atmospheric ^{14}C activity during the 1950s and early 60s, and its subsequent decline, has provided the ideal dating tool for forensic studies, often allowing for samples to be dated within 1-2 calendar years during the periods of steepest curve (1960s-1970s). The technique has been applied to a range of forensic cases, including determination of vintages of wine (e.g. Zoppi et al. 2004), verifying modern art (e.g. Caforlio et al. 2014) and the detection of fossil fuels in biofuel products (e.g. Dijs et al. 2006). The technique is particularly important for forensic scientists needing to identify a year of birth and/or death for human remains, or simply to determine whether the remains of a deceased date to ancient or recent times. Such information can be vital in cases of accidental discovery of human remains and where little contextual information is available and police need to investigate whether the remains are of forensic interest or archaeological in origin. In particular, when human remains are found and there is a need for identification, radiocarbon dating can assist with narrowing the list of missing persons to which those remains could belong.

2. Forensic radiocarbon dating of human remains

Traditional anthropological methods can provide a relatively accurate age at death for juvenile skeletal remains (Reventlid et al. 1996; Scheuer & Black, 2000) but are less accurate in adult or 'mature' individuals. The older the individual, the wider the age range given by the methods, often providing no more than 'adult' or, for example, 'older than 40 years' (Cook et al., 2015, and references therein). Further uncertainties can be encountered if the remains are incomplete or poorly preserved due to a series of post-mortem (taphonomic) factors, occurring between the death of the individual and the discovery of the remains. Radiocarbon dating of human remains can provide information that traditional approaches may not. For example, with incomplete remains where there is no presence of artefacts, or if the context in which the remains have been found is of little use or poorly documented, or if the recovery has been poor due to the absence of a forensic archaeologist.

Modern (i.e. post 1950 AD) radiocarbon measurements are reported as $F^{14}C$ (fraction of modern ^{14}C where a value >1 would indicate post-1955) (Reimer et al. 2004), although sometimes as pMC (percent modern carbon) in

older publications. Five modern calibration curves currently exist (3 for the northern hemisphere and two for the southern hemisphere), based on data from tropospheric records, tree-ring series and measurements on other organic materials from 1950 to 2011 (Hua et al. 2013). The data are mostly collected from clean-air sites, away from most human activities, so avoiding nuclear installations and fossil fuel discharges. As most nuclear weapons testing was carried out in the northern hemisphere large gradients in radiocarbon activity existed from north to south and high to low latitudes during the early bomb period (mid 1950s to late 1960s) (Hua et al 2013). However, due to wind currents and related factors, variations in global environmental ^{14}C values are fairly minimal throughout most of the bomb period (Ubelaker et al. 2015).

These calibration datasets are included in calibration software packages, such as CALIB and OxCal. The nature of the bomb spike means that unless the date is from the 1963 apex, there are normally a minimum of two calibrated date ranges for each modern radiocarbon date. Figure 1 shows an example date of $F^{14}C = 1.22086 \pm 0.00359$, calibrating to two time periods: 1959-1961 AD (29.8% probability) and 1983-1985 (65.6%). Additional information is therefore usually required to determine whether a date corresponds to the ascending or descending slope of the curve.

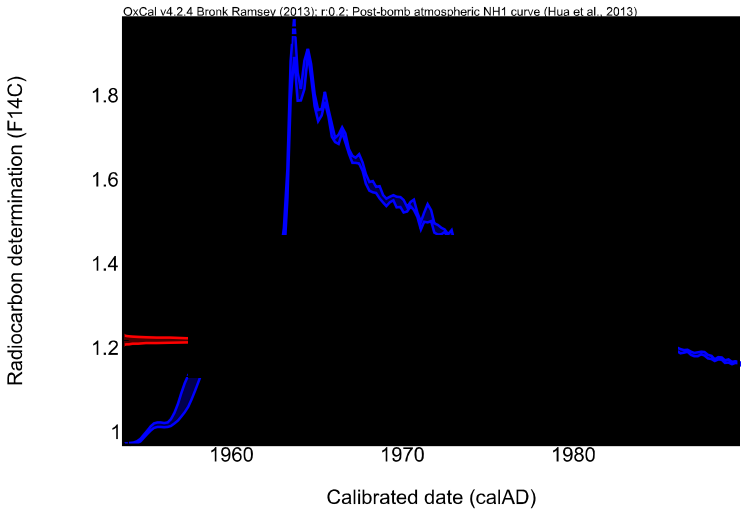

Fig. 1. Example calibration plot for a modern sample with an $F^{14}C$ value of 1.22086 ± 0.00359. The date is calibrated using OxCal v. 4.2.4 and the post-bomb atmospheric NH1 curve (Hua et al. 2013)

While alive, all living organisms assimilate ^{14}C and the radiocarbon levels of their tissues reflect both the atmospheric concentrations at the time, as well as their dietary input. At the time of death, an organism stops taking in radiocarbon and, theoretically, measurement of its radiocarbon activity could be used to indicate time of death. However, different tissues have different turnover rates for carbon, depending on the specific tissues and the age of the individual. Additionally, all tissues will have a time lag relative to atmospheric concentrations due to the time taken for radiocarbon to enter plant material via photosynthesis and progress along the food chain.

Carbon turnover is most rapid in soft tissues, with recorded time lags between atmospheric levels and human brain tissue of just a few months (Libby et al. 1964), 1.1 years for blood and 1.8 years for lung tissue in adults (Broecker et al. 1959). Nydal et al. (1971) found close agreement between atmospheric radiocarbon activity and measurements made on hair and blood samples. Harkness and Walton (1972) analysed a suite of tissues from a 37-year old female who died in 1969 and observed the highest radiocarbon levels in brain, followed in decreasing order by muscles, ovaries, kidneys, liver, fat, uterus, bone marrow, bone collagen and bone minerals. Stenhouse and Baxter (1977) recorded lags of 6 years for bone marrow, while other studies observed even greater lags for cartilage and bone collagen. Several early studies (e.g. Harkness and Walton 1969, 1972; Stenhouse and Baxter, 1977) suggested that given this time lag, radiocarbon dating was not suitable for accurately dating modern forensic specimens, despite its suitability for archaeological specimens.

However, subsequent studies since the late 1980s (e.g. Taylor et al., 1989; Wild et al., 2000; Cook et al., 2015) have demonstrated the importance of radiocarbon dating to forensic studies. The choice of tissue for dating forensic cases is influenced by two main factors: the age of the individual at death and the specific tissues available for dating. For new-born babies and children who have not yet reached the end of puberty, most tissues will have ^{14}C levels that match those of the atmosphere at the time of their death (e.g. Wild et al. 2000). For adults, the turnover rate of different tissues is an important consideration, with hair, nails or soft tissue often preferred for dating, if available, due to their rapid

turnover and hence assumed close relationship with atmospheric radiocarbon levels at the time of death.

Wild et al. (2000) reported a case study initiated by a Viennese court, following the finding in 1992 of the remains of two elderly sisters who had evidently been dead for a long time, possibly several years. Wild et al. (2000) initially tested hair, bone collagen and lipids, and bone marrow from four individuals with known dates of death to test the applicability of the technique before dating material from the two sisters. They recorded time lags between the real time of death and calibrated dates of death of 1-2 years for hair and bone lipids and therefore recommended these tissues for dating the time of death in forensic cases. Lags of 20-30 years were observed for long bone collagen, which was therefore deemed unsuitable for the purpose of identifying date of death.

Hodgins (2009) reported radiocarbon measurements on 9 different tissue fractions (tooth enamel, bone apatite, bone collagen, bone lipid, skin collagen, skin lipid, hair, nails and blood) from 36 humans who died in 2006 in south-eastern USA, and whose birth dates were known. At the time of the study, atmospheric data were only available up until 2003, so the calibration curve had to be extrapolated. Blood, hair and nail specimens were found to lag atmospheric radiocarbon levels by 0-3 years, with no evidence of variability due to genetic or dietary factors. All samples were from the same geographical location and hence may not have been expected to demonstrate such variability.

However, recent work by De La Torre et al. (2014) has suggested that modern human hair can often be contaminated with petroleum-based (i.e. radiocarbon-depleted) carbon, found in most hair care products, resulting in hair samples producing older dates than nail specimens from the same individual. These compounds are often designed to penetrate the hair cuticle, and both conventional and more sophisticated radiocarbon pre-treatment protocols are unable to remove them fully (Santos et al. 2015). It is therefore recommended that fingernails are the most suitable human tissue for year-of-death estimations.

In many instances, soft tissues are not available for forensic analysis and only bone tissue remains. Radiocarbon dating of bone normally occurs by the extraction of what is referred to as collagen, but which usually contains a wide range of amino acids, short-chain peptides and other proteins, as well as collagen

(Brock et al., 2013). Bone collagen is suitable for dating archaeological samples that are between a few hundred and many thousands of years old (up to the limit of radiocarbon, ca. 50,000 years), being relatively decay resistant in many environments, and containing a relatively high concentration of carbon. Also, collagen does not have the same issues as bone mineral carbonate which is known to exchange carbon with the depositional environment over long periods of time, which can result in erroneous age measurements.

However, the turnover of collagen is a complex subject and is affected by many factors, including diet, disease and the influence of associated medications such as bone growth promoters Geyh (2001), stress factors, type of bone, and age. While this turnover has little effect on archaeological samples, it is not advantageous for forensic specimens. Several studies have recorded time lags between atmospheric radiocarbon levels at the time of death and measurements on bone collagen of up to 20-30 years for mature adults, regardless of their age (e.g. Stenhouse & Baxter, 1977; Wild et al. 2000; Ubelaker et al. 2015 and references therein).

2.1. Estimating date of death

Bone is constantly remodelled during adulthood, with the rate of remodelling decreasing with increasing age (Hedges et al. 2007). Recycling of bone carbon also becomes a factor with advancing age, with radiocarbon from existing skeletal material being incorporated into new bone formation, increasing the time lag between atmospheric and dietary carbon sources and bone collagen. Resorption and synthesis often occur in discrete locations within specific bones, and hence radiocarbon activity may vary across an individual bone (Shin et al. 2004). Additionally, osteoporosis can discontinue completely the incorporation of new carbon into bones as osteoblasts (bone forming cells) become inhibited and simply recycle old carbon (Shin et al. 2004). The onset of such rapid bone loss can vary with age and sex, but tends to start in postmenopausal women at around the age of 40-50 years, and 20-30 years later in men. It is entirely possible that an 85-year old woman with osteoporosis may have ceased to add new carbon to her bones since her mid-50s, while a 72-year

old man, for example, may continue to turn over bone carbon and possibly show no sign of osteoporosis (Shin et al. 2004).

Turnover rates are known to vary between different types of both cortical and trabecular bone (Parfitt, 2002). Differences in turnover have been observed within regional locations of subperiosteal, intracortical and subendocortical bone, and are also expected between cancellous bone associated with yellow or fatty marrow compared with that located with red or hematopoietic marrow (Parfitt, 2002).

The prolonged delay periods of up to 20-30 years between radiocarbon measurements of collagen from individuals with known dates of death and atmospheric levels at the same time (e.g. Stenhouse & Baxter, 1977; Wild et al., 2000; Ubelaker et al. 2015 and references therein) have led some to conclude that bone collagen is not a suitable tissue for time of death analysis. However, many of the studies either do not state which bone was analysed, or sampled femoral cortical bone, which is now known to have a long turnover time. The sampling of femoral material may, in some instances, be due to limited available material, for example, where incomplete skeletons are found, or because of the difficulties in accessing known-age samples for detailed analysis. The largest study of radiocarbon measurements on modern human bone was published by Hedges et al. (2007), who analysed femoral mid-shaft collagen provided by the Melbourne Femur Collection from 67 individuals of both sexes, who died in Australia aged between 40 and 97 years old, between 1990 and 1993. This study found that human femoral bone collagen isotopically reflects an individual's diet over a period considerably longer than 10 years and includes a significant proportion of collagen synthesised during adolescence.

Another possible reason for the selection of the long-bone for dating individuals may be that mid-shaft cortical bone is often preferred when sampling archaeological specimens, as it is usually denser, with better collagen preservation and less sedimentary contamination than more porous trabecular bone. The significance of the difference in turnover time between different bones, when dating forensic specimens, may not have been appreciated for early studies.

To investigate the time lag observed in bone collagen samples, Ubelaker et al. (2015) compared radiocarbon measurements on bone collagen from 39 individuals from several studies (Hedges et al., 2007; Hodgins 2009; Ubelaker et al. 2006; Ubelaker and Parra, 2011; Wild et al. 2000) with published atmospheric values corresponding to the geographical area in which each individual was located. All bones analysed were either described as cortical (femur) or undefined 'bone', and the radiocarbon measurements were analysed for each decade of life. The data suggested that time lag increases with age, from a minimal lag of ca. 3 years for individuals between the ages of 10 and 19 years to a peak of ca. 31 years for individuals aged between 60 and 99 years old (with little variation within that 40 year period). The authors tentatively proposed that this average time lag could be applied to radiocarbon measurements on bone collagen for determination of date of death, but stressed that more data were required to verify this.

However, trabecular bone is known to have a faster rate of turnover of collagen than cortical bone (e.g. Manolagas and Jilka, 1995; Parfitt, 2002) and so theoretically, a radiocarbon date on trabecular bone is likely to be closer to atmospheric levels at the time of death than a date on cortical bone. Ubelaker and Parra (2011) dated femoral cortical bone and vertebral trabecular bone from 4 human adults from Andean Peru, all with known birth and death dates. While the measurements on cortical bone had a lag of 11 years with known atmospheric radiocarbon levels for individuals aged 27, 44 and 56 years, the time lag with trabecular bone was minimal, up to just three years. Although this is a small dataset, it does indicate that dating trabecular bone may provide a more reliable date of death for an individual, especially those up to the age of 50 years old, than associated dates on cortical bone collagen. However, Cook et al. (2015) observed a date on trabecular bone from a vertebra lagged that of a date on cortical bone from the femur of the same individual by approximately 1 year. In this case, the individual was thought to age between late teens and early 20s and according to the results of Ubelaker and Parra (2011) should show a minimum difference between the two bone types. The authors concluded that in hindsight, they should have analysed trabecular and cortical bone collagen from the same bone to obtain a better comparison of ^{14}C activities.

The role of diet is known to influence the time lag between radiocarbon measurements made on collagen and corresponding atmospheric levels. Dietary influences will vary locally, with local variations in ^{14}C levels in the atmosphere and foodstuffs affected by natural processes and human activity. Food of local terrestrial origin has a delay of approximately 1 year from atmospheric radiocarbon levels (Hua and Barbetti, 2004). Most human diets contain terrestrially grown vegetal and meat products, but the proportions of each can vary significantly between different locations. The time taken for atmospheric radiocarbon to be consumed by humans via vegetal material is naturally shorter than that taken for meat products, due to the additional step(s) in the food chain. Therefore, an individual with a high meat input in their diet may have a slightly greater time lag between their tissues and atmospheric radiocarbon levels than a vegetarian or one with low meat consumption.

However, many human diets also rely on fish and seafood, with significant variations geographically. Marine resources (and some freshwater ones) contain older radiocarbon due to ^{14}C offsets between reservoirs and the terrestrial biosphere; post-bomb marine radiocarbon datasets show a great deal of regional variation (Reimer et al. 2004). Therefore, consumption of these marine and freshwater resources has the potential to influence the radiocarbon date of an individual by several years. For example, Georgiadou and Stenström (2010) determined that a diet containing 8% fish from the Barents Sea altered the radiocarbon age of an individual by around -2.4 to +1.4 years. In the same study, they calculated that an individual who consumed fish from close to the Sellafield nuclear fuel reprocessing plant in Cumbria, NW England, would have an $F^{14}C$ value that reflected a shift of -26.3 years. The potential impact of a local diet must therefore be considered when dating modern individuals.

During analysis for radiocarbon dating, $\delta^{13}C$ and $\delta^{15}N$ values are often routinely measured, or can be measured at little extra cost and time. Such values can be useful as they provide an indication of an individual's dietary input, and will highlight a diet that could potentially affect the radiocarbon date: as the proportion of marine resources in the diet increases, both the $\delta^{13}C$ and $\delta^{15}N$ values increase. The percentage of marine resources is often determined by a linear interpolation between $\delta^{13}C$ end members of -12.5‰ for an individual with

a 100% marine diet and -21.0‰ for someone with a 100% terrestrial diet (Arneborg et al. 1999). The $\delta^{13}C$ bone collagen value for the forensic specimen can then be placed on the linear function to determine the percentage marine diet.

2.2 Estimating date of birth

Some tissues do not turn over carbon during an individual's lifetime and can therefore be used to provide a year of birth, and this information can be a significant aid to investigators when the identification of a deceased individual is unknown. One such tissue is the eye lens crystallines, which are thought to form during early embryonic life, and which have been demonstrated to provide a date of birth with the accuracy of a few years (Lynnerup et al., 2008; Kjeldsen et al. 2010).

The carbon in tooth enamel is laid down in young children during crown formation and has been shown not to turn over during an individual's lifetime (Spalding et al. 2005). The crown of each tooth is formed at distinct, well-defined time periods after birth, depending on tooth number and gender (e.g. Nolla 1960; Bolaños et al. 2000), and can thus be used as a powerful tool for estimating the date of birth of an individual.

Tooth enamel contains less than 1% carbon as carbonate within the apatite structure and, like bone mineral carbonate, is not typically dated in archaeological specimens because of the likelihood of exchange over time with carbon of different ages in the depositional environment (Hedges et al. 1995). However, such exchange appears not to occur on the timescale involved in modern forensic cases (Spalding et al. 2005). Teeth will also survive heat and chemical degradation better than bone and other human tissues, making them in some instances the only available tissue for dating.

Spalding et al. (2005) determined dates of birth of 22 individuals to within 1.6 ± 1.3 years using tooth enamel, and demonstrated that dating two different teeth from the same individual that formed at different times can resolve the ambiguity of which side of the bomb peak the results fall. By using the upper limit of enamel formation (i.e. the time by which enamel formation was

complete), the lag period between atmospheric radiocarbon levels and incorporation into the tooth can be balanced out (Buchholz & Spalding, 2010)

Atmospheric nuclear weapons testing occurred in a limited number of locations in the northern hemisphere. Alkass et al. (2011) dated enamel from 95 teeth from 84 individuals of known birth date, who were raised in 8 different countries on 4 different continents in both the northern and southern hemispheres, and observed that geographical location did not affect the precision of radiocarbon estimations of the year of birth.

Cook et al. (2006) proposed that an unambiguous year of birth could be determined from a single tooth, by dating both the enamel and the combined collagen from the dentine and cementum. Similarly to enamel, dentine has been shown by amino acid racemization not to turn over during an individual's lifetime (Ohtani et al., 1995). The crown enamel forms before the root, and hence the two dates on a single tooth can identify whether the date lies on the ascending or descending slope of the bomb peak. Cook et al. (2006) analysed 8 teeth from different individuals of known birth year and produced results that were accurate to within 1-2 years. One advantage of dating collagen from a tooth is that it can provide $\delta^{13}C$ and $\delta^{15}N$ values to indicate any unusual dietary input that might affect the date.

Kondo-Nakamura et al. (2011) also derived unambiguous ages on a single tooth by measuring the radiocarbon concentrations in enamel from the occlusal and cervical regions of a single tooth, as they form at different times.

Ubelaker and Parra (2011) highlighted that dental development does vary globally and stressed the importance of using tooth enamel formation data relevant to the individual being examined. It has also been suggested that calibrating dates on teeth, in particular, would be more accurate if using a database of measurements from known regions and from teeth obtained from people with known years of birth. However, such a dataset would require a significant number of dates from a large range of geological regions.

3. Published case studies

Given a single date on a single sample, e.g. an individual bone, it is impossible to get any clear information other than to state whether or not the

individual lived pre- or post-bomb. However, this is often sufficient to provide an investigation with sufficient perspective into the level of enquiry required following the finding of human remains.

For example, Taylor et al. (1989) were approached by several coroners' offices in California to investigate five different cases. They identified two individuals as having a nuclear bomb-pulse signal – i.e. 'modern' – and therefore of interest for further investigation by the coroners. The absence of bomb ^{14}C in the other samples indicated that the individuals were likely to have died before 1950, and so were excluded from further investigation. They classed bone samples for the recent past into 3 time segments: (1) a pre-1650 period (non-modern), (2) a 1650 -1950 period (pre-modern) and (3) a post-1950 period (modern), i.e. bomb period - this being the period of interest.

Ubelaker and Houck (2002) reported the strange finding of a disarticulated human cranium and mandible partially encased in strong plastic within two buckets in a riverbed in Pennsylvania, USA, in 1999. Anthropological analysis indicated a male of African ancestry with age at death over 50 years. Cardoso et al. (2012) similarly reported radiocarbon dating of human skeletal remains found in a shallow grave during the building of a hospital in northern Portugal. In both instances, radiocarbon dating indicated a lack of bomb-pulse carbon, and that the individuals had therefore died before the mid-1950s and that further investigation of the remains by the police was not necessary. Fournier and Ross (2013) reported three further cases where a single radiocarbon date was sufficient to elucidate whether or not a find was of forensic significance or historical.

Several published case studies demonstrate the usefulness of acquiring radiocarbon measurements on more than one skeletal component from an individual, in particular for determining which side of the bomb peak the dates correlate to. For example, Ubelaker et al (2006) dated dental, cortical and trabecular samples from two adult individuals born in the 1920s who were known to have died in 1959 and 1995. In both cases, the dental results correlated to pre-bomb levels as expected. The date for the cortical bone from the individual who died in 1959 was also pre-bomb, allowing the date of the trabecular bone (1.031 $F^{14}C$) to be place on the ascending slope of the bomb

curve. For the individual known to have died in 1995, the values were higher for the trabecular bone than the cortical bone (1.140 and 1.131 $F^{14}C$, respectively), hence identifying the pre-1963 side of the bomb curve (and indicating a large time lag between the collagen and atmospheric radiocarbon levels at the time of death).

The most extensive case study of the skeletal remains of a single human individual was published by Cook et al (2015). Female human remains were found by builders in a car park in Manchester, UK, in 2010. However, they were challenging in a forensic anthropological sense as there were a limited number of areas to observe due to loss and damage. The inclusive age range was estimated to be between 18 and 75 years. However, epiphyseal fusion tended to suggest that this individual was at the lower end of the range, with one method estimating the maximum age to be 27. On this basis, females between 18 and 30 were deemed to be of the highest priority in the missing persons' investigation. Radiocarbon measurements were made on crown enamel and root collagen from three teeth (lower canine, lower lateral incisor and upper third molar) as well as collagen from cortical (femur) and trabecular (vertebra) bone. The dates from the teeth suggested a year of birth between 1950 and 1954, and the bone dates indicated the year of death to be between 1969 and 1974, thus confirming the younger estimate of the age.

4. The Future for Forensic Radiocarbon Dating

The precision of modern bomb-pulse radiocarbon dates was greatest in the 1960s and 1970s, when the peak was declining steeply, but this precision has progressively decreased since then as atmospheric radiocarbon levels approach pre-bomb levels. It is likely that atmospheric radiocarbon concentrations will drop below pre-1950 levels within the next few decades, but what are the implications of this for forensic radiocarbon dating of human remains?

Anthropogenic influences since the 18th and 19th centuries have seen the radiocarbon activity of atmospheric CO_2 vary as a result of nuclear weapons testing and fossil fuel burning, as well as natural CO_2 cycling between atmospheric, oceanic and terrestrial carbon reservoirs. Now that nuclear testing is well and truly over, in the 21st century, the radiocarbon activity of atmospheric

CO_2 will most likely be determined by the amount of fossil fuel burning (as the release of carbon dioxide acts to dilute atmospheric ^{14}C, artificially 'aging' the atmosphere), and how this effect is moderated by natural exchanges with the oceans and the terrestrial biosphere (Caldeira et al. 1998; Graven 2015).

Graven (2015) ran models simulating future $^{14}C/C$ ratios in atmospheric CO_2 scenarios, based on the Inter-Governmental Panel on Climate Change (IPCC) 5th Assessment Report for Atmospheric Emissions. Ambitious fossil fuel emission reductions could sustain $^{14}CO_2$ levels near to preindustrial levels until 2100. However, using the 'business-as-usual' scenario, atmospheric ^{14}C concentrations will drop below 1950 levels by 2030, and maybe as soon as 2019 using the rapid scenario. After this time, predicted trends diverge depending on future fossil fuel trends, but due to the release of ^{14}C-dead carbon by fossil fuel burning, newly produced organic material will appear 'aged'. Given current trends, it is likely that artificial ageing of the atmosphere will be much faster and with a larger magnitude than previously expected (Graven, 2015).

Once the atmospheric radiocarbon activity drops below that of 1950 AD, samples will have the same levels of ^{14}C as objects from the last few centuries. For example, a sample from 2050 AD may have the same radiocarbon date as something from 1050 AD, and a sample from 2100 AD may give a similar date to something from 100 AD (Graven, 2015). Therefore, investigators will, at the very least, require additional contextual and taphonomic information to resolve this ambiguity, and confirm that a sample is from the 21st century rather than being an historical artefact.

Given these potential scenarios, it is likely that the slope of the curve will be steeper than in the pre-bomb era, and will hence provide more refined calibrated date ranges than in historical times, but not at the level of precision observed during the steepest parts of the bomb spike, in the 1960s and 70s. Hence, the subtleties of dating both cortical and trabecular bone from the same individual, or different teeth or dentine/enamel pairs may be lost within a broader calibrated date range.

It should also be considered that these predictions rely on a single climate change scenario. If global emissions were to switch between different scenarios – e.g. from business-as-usual to a more rapid or much slower emission rate, it is

not impossible that atmospheric ^{14}C levels would fluctuate, resulting in a period similar to the pre-modern period of 1650-1950 AD, where dates are indistinguishable using radiocarbon.

Therefore, it is possible that there may be an 80-year time period, from 1950 AD to circa 2030 AD, where radiocarbon dating has the greatest potential for forensic science, for individuals that were born and/or died within that period. Even for those that die after the drop below pre-1950 levels, the radiocarbon date of a tooth will still be useful for year of birth information for several decades. However, for individuals born after ca. 2030 (and this drop), radiocarbon dating will become significantly less effective a technique for the forensic sciences.

4. Conclusions

Radiocarbon dating is a valuable tool for dating human remains. It is currently possible to yield accurate information relating to the year of birth and/or death of an individual. In the absence of soft tissues, fingernails are the most suitable tissue for identifying the year of death (as long as additional information is available to identify which side of the bomb peak the date corresponds to). Trabecular bone collagen appears to provide a more accurate date of death than collagen from cortical bone, but dating both allows placement of the dates on the correct side of the bomb curve. Radiocarbon dates on teeth have been demonstrated to provide accurate estimates of the year of birth, either by dating two different teeth known to have formed at different times after birth, or by dating the crown enamel and dentine collagen from a single tooth or different areas of enamel from the same tooth.

However, in the future, the use of radiocarbon for forensic analysis will be less effective, especially in the second half of the 21st century and beyond, as atmospheric radiocarbon levels reach pre-bomb levels. When $^{14}CO_2$ concentrations drop below that of 1950, additional evidence will be required to eliminate historical individual remains, and dating precision will be reduced.

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