Radiocarbon dating of skeletal remains

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The background of this study dates back to 2013. In November 2013, thousands of human skeletons were found at a construction site in Hyehwa-dong, Seoul and referred to the National Forensic Service, where I was working at that time. CT scan, autopsy, forensic anthropologic examination, forensic odontologic examination and DNA analysis were carried out, and these skeletal remains were assumed to be bodies for anatomical training of medical school students. The main concern at this stage was whether these bodies were before or after Korea’s independence, and radiocarbon analysis was the only way to solve this problem. Unfortunately, the effects of formalin used for the preservation of the body limited the analysis and ultimately the problem was not solved. However, in this process, we found out that radiocarbon analysis is useful for dating of the skeletal remains, and this study was designed to examine whether it can be applied to practical applications.

This research could be done with the help of several people. Professor Nak Eun Chung, who oversaw the work on Hyehwa-dong's skeletal remains and designed the research, Mr.

Seung Gyu Choi who took charge of sample collection and pre-treatment and assisted the whole research, Mr. Jeong Uk Seo helped with pretreatment of teeth, Professor Dae-Kyoon Park, a forensic anthropologist who proposed the radiocarbon dating, Dr. Sang-Seob Lee, a forensic odontologist who gave advice on the development of teeth, Dr. Kyu-Joon Park of the Korea Institute of Geoscience and Mineral Resources (KIGAM), who conducted radiocarbon analysis and advised on this method and with the help of several other colleagues, the work was completed.

This is kind of embarrassing, but I needed seven years to complete my doctoral dissertation. In the process, the research topic has changed several times and I delayed the research schedule promised by personal circumstances. I thank my academic advisor, professor Se Hoon Kim who encouraged me without giving up.

I also thank my parents for believing and watching me silently, and my parents-in-law for helping me both physically and spiritually.

Lastly, I would like to express my sincere gratitude to my wife, Yoo Jin Kim, who has been dedicated to her husband's dissertation while she was also busy fulfilling her dream, and to my son, Zuan Park, who gave me strength whenever I was tired although he is still young and not sure what this mention means.

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ABSTRACT

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Identifying remains is an important role of forensic medicine. Information such as age, sex, and height is used to verify the identity of the deceased and can be obtained through current technology. However, dating, i.e. estimating the birth year and death year, has not yet been practically applied. A dating method using radiocarbon analysis was recently introduced and studies to apply it to human tissues have been reported. The purpose of the current study is to confirm the applicability of radiocarbon dating for the identification of skeletal remains and to develop formulas to estimate the birth and death year.

Twenty autopsy cases from the National Forensic Service in Korea, from January to December 2015, with known birth year and death year were selected for inclusion in this study. And four autopsy cases of previous study were also included for the statistical analysis. For each case, three samples were taken: dentin of the first molar in mandible, spongy bone of the femur head, and the compact bone of the femur midshaft. For each sample, radiocarbon analysis was carried out and the corresponding estimated birth year and death year were calculated using the bomb peak curve. The differences between the estimated birth year and the actual birth year, and the estimated death year and the actual death year were determined and analyzed on the influence of age and sex variables. A formula for estimating the birth year and death year was developed and the applicability of the formula was determined.

The results showed that the difference between tooth year and birth year was 4.8 years on average, and the difference between death year and femur head year was 11.3 years on average. In male, the difference between death year and femur head year increased with age, however, it did not show any difference according to age in female and sex.

The estimation formula of death year obtained from femur radiocarbon analysis had low explanatory power (R^2=0.842), and so it was not enough to apply in practice. The estimation formula of birth year obtained from tooth radiocarbon analysis had a relatively high explanatory power (R^2=0.996), however, the error varied according to the section of the bomb peak curve applicable.

This study has insufficient number of analyzed samples to obtain an accurate estimation formula. However, it is meaningful because it is the largest single study of its kind, to date, and uses specific and identical skeleton (first molar in mandible and femur head/femur midshaft) to increase the accuracy of analysis.

Key words : radiometric dating, forensic anthropology, tooth, femur

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I. INTRODUCTION

Autopsies of skeletal remains are performed frequently and sometimes attract social attention. According to the National Forensic Service, which is responsible for legal autopsy in Korea, the number of autopsy cases in the state of skeletal remains steadily increased from 55 in 2012 to 145 cases in 2017 (Table 1).[1-6] In the past, information obtained by autopsy of skeletal remains was insufficient to be highly useful to investigative agencies. However, in recent years, autopsy of skeletal remains has yielded useful information which can facilitate investigation into the death. This may account for the increase in skeletal autopsies referred to the National Forensic Service by investigative agencies.

Table 1. Decomposition and skeletonization among unknown cause of death

Year	2012	2013	2014	2015	2016	2017
No. of decomposition	236	211	176	403	607	754
No. of skeletonization	55	47	58	88	135	145

The forensic work for skeletal remains is divided into investigation of the cause of death and identification. Due to decomposition and skeletonization, investigation of the cause of death is limited to examination of injury, such as fractures, and toxicological analysis. Identification of the deceased relies on anthropological examination, odontological examination, and DNA analysis. Sex and height can be determined through anthropological examination. Sex can also be determined through genetic testing. Age may be determined through odontological examination. If a sample related to a putative person is accessible, judgment can be made as to whether or not the subject has the same. In addition, techniques for dating skeletal remains are currently under investigation.

Dating is used to estimate the birth year and death year of skeletal remains. Comparing a case born in the 1950s who died in the 1980s, and a case born in the 1980s who died in the 2010s, the targets for investigation are different. The dating of skeletal remains provides useful information to the investigative agency because it is able to place the deceased in an estimated time context (Fig.1).

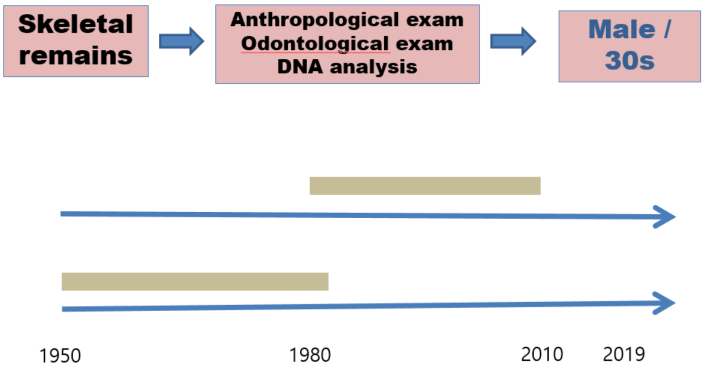

Figure 1. The necessity of dating for skeletal remains.

Methods for the dating of the skeletal remains include fluorescence test by ultraviolet light, serological methods such as the detection of hemoglobin, the Coombs test and luminol technique, and chemical methods such as measuring of the proportion of nitrogen and the detection of specific amino acids.[7] The majority of these methods are not enough for practical application. However, the methods for estimating birth year by analysis of racemization of specific amino acid in teeth dentin are relatively accurate and have been recommended for practical application the field.[8] However, the application of this method is limited because the same teeth with known birth year are required for examination. The remaining methods are not reliable enough for practical application. Recently, a novel dating method using radiocarbon analysis has been proposed and various studies are underway to determine its usefulness in the field.

Isotopes are variants of a particular chemical element which differ in neutron number, and consequently in nucleon number (mass number). All isotopes of a given element have the same number of protons but different numbers of neutrons in each atom. Carbon-12(^{12}C), carbon-13(^{13}C), and carbon-14(^{14}C) are three isotopes of the carbon element with the respective mass numbers 12, 13, and 14. The atomic number of carbon is 6, which means that every carbon atom has six protons, so that the neutron numbers of these isotopes are 6, 7, and 8, respectively. Radioactive isotopes are referred to as radioisotopes and isotopes which have never been observed to decay radioactively are referred to as stable isotopes. ^{14}C is a radioactive form of carbon, whereas ^{12}C and ^{13}C are stable isotopes. ^{14}C is also called as radiocarbon and present in nature at very low rates compared to ^{12}C and ^{13}C. ^{14}C is produced in the atmosphere at high altitude (9,000 – 15,000 m) by nuclear reaction (n-p reaction) between nitrogen atoms and thermal neutrons which are secondary products of cosmic rays, and is converted to ^{14}N by beta decay with a half-life of 5,730 years. Carbon atoms present in nature are mainly used in photosynthesis by plants in the form of carbon dioxide, and are metabolized in the body of plants and animals where they are used as energy sources. The ratio of carbon isotopes in the air is equally reflected for the organisms of the time and the region (Fig.2).

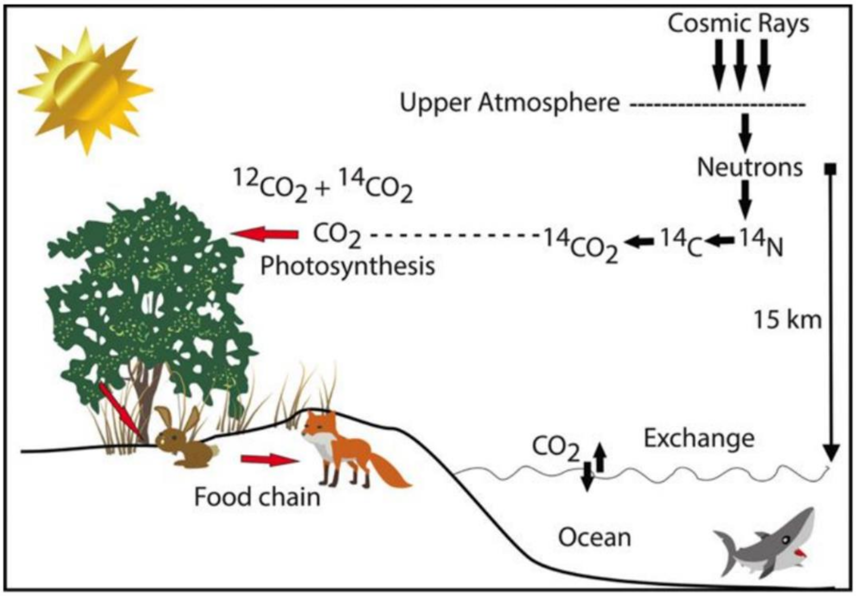

Figure 2. Radiocarbon cycle in the atmospheric and biosphere.[9]

Radiocarbon dating was developed in the 1940s and is used to prove the authenticity of artifacts or historical findings up to the age of 50,000 years. Although this technique can be applied to human skeletal remains that are presumed to be ancient, due to the large error margin, current radiocarbon dating techniques are not useful for remains under 100 years old. Therefore, this technology has limited application in the field of forensic medicine for current-day cases under investigation. However, after the 1950s, the amount of atmospheric ^{14}C increased significantly worldwide because of atomic bomb tests. The amount of ^{14}C reduced after 1964 thanks to the Nuclear Non-Proliferation Treaty (Fig.3). Knowledge about the worldwide ^{14}C levels at given points in time can be applied across numerous fields, for example to verify and authenticate works of art or to estimate the year of production of wine. Research has been carried out to apply this understanding of atmospheric ^{14}C levels to the dating of human skeletal remains.

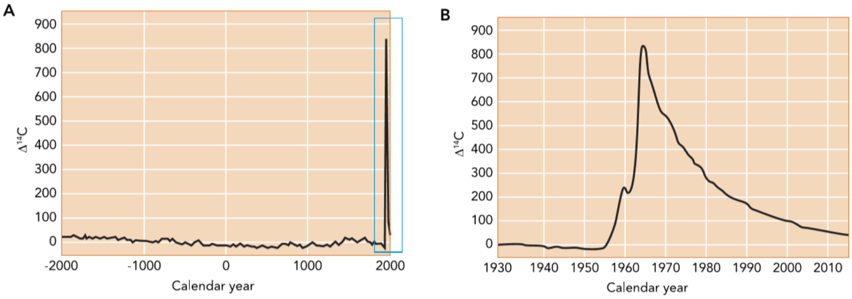

Figure 3. ^{14}C concentration change in the atmosphere. A: the levels of ^{14}C in the atmosphere have been relatively constant over the last thousand years. B: Bomb peak curve.[10]

Since the late 1980s, the bomb peak curve has been applied to forensic problem solving and has been practically applied in the field. Taylor et al.[11] reported the use of radiocarbon to identify human skeletal remains. Jull et al.[12] focused on bone and found uptake was complex. Wild et al.[13] measured several soft tissues and found that the ^{14}C content of hair lagged approximately one year behind atmospheric ^{14}C levels. Spalding et al.[14] and Nakamura et al.[15] carried out research with teeth to estimate birth year. Santos et al.[16] estimated the death year with human hair and fingernails and report that fingernails are a good source of keratin protein. Garrido-Varas et al.[17] examined the death year with soft tissue and bone.

The dating of human skeletal remains is generally performed by analyzing teeth to estimate the birth year, and analyzing bones to estimate the death year.

Once a permanent tooth is formed, it is maintained until death. The first molar in the mandible begins developing during gestation, and erupts as a permanent tooth around 6 years of age. Its root is complete by 9-10 years of age.[18] Therefore, a person can be assumed to have been born several years earlier than the estimated age of teeth sample by the radiocarbon analysis. Teeth consist histologically of enamel, which covers the crown surface, and dentin, which makes up the majority of the tooth (Fig. 4). In previous researches, enamel was mainly used for radiocarbon analysis. Enamel is produced before dentin and is composed of 96% minerals, 4% organic material, and water. Dentin formation is completed at the time of root completion. Dentin, which consists of 70% mineral, 20% organic material, and 10% water, has a larger volume per tooth than enamel.

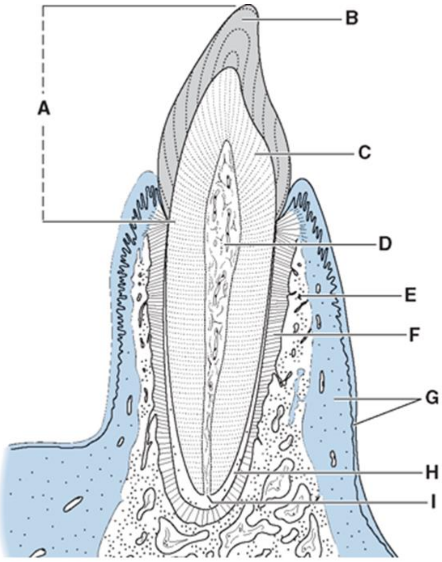

Figure 4. Schematic diagram of a tooth. Labeled component include the crown(A), enamel(B), dentin(C), pulp(D), alveolar bone(E), periodontal ligament(F), gingiva(G), cementum(H), and apical foramen(I).[19]

In adults, the volume of bone is constant. This is because bone formation and bone resorption occur simultaneously. About 10% of the bone matrix is remodeled every year.[20] The ratio of newly remodeled bone matrix is called the turnover rate, and it depends on age, sex, and bone type. Generally bone formation decreases as age increase, and in women osteoclastic activity increases after menopause because estrogen inhibits IL-1, TNF, M-CSF & IL- 6 which activate osteoclasts. Sponge bone has a shorter turnover rate than compact bone. So the result of the radiocarbon dating of the femur head is closest to the death year and it can be inferred that a person died a few years after the carbon dating value.[21,22] Manolagas and Jilka[23] report that about 25% of adult spongy bone is replaced annually as opposed to about 3% of compact bone. Leggett[24] reports that the more rapid turnover in spongy versus compact bone is due to the high density of osteoblasts and osteoclasts per unit area. Among the bones, the femur is primarily used for radiocarbon dating because the head part contains sponge bone and the body part contains compact bone. Thus, the death year can be estimated by comparing the two results. To accurately estimate the birth year and death year, there are some points to be supplemented.

The purpose of this study was to increase the accuracy of the dating of the human skeletal remains by radiocarbon analysis. Analysis was conducted using the tooth samples (first molar in the mandible), for estimation of birth year; and femur head and femur midshaft samples for estimation of death year. Dentin was analyzed instead of enamel because of its advantages, and its usefulness was evaluated. Finally, estimation formulas for birth year and death year were developed and validated.

II. MATERIALS AND METHODS

This study was performed on autopsy cases conducted at the National Forensic Service from January to December 2015. The study included cases that were skeletonized and birth and death years were correctly identified and cases that died from a fall or traffic accident and no additional incision was needed to collect samples due to severe injuries. And cases of previous study[25] carried out in 2014 were included in the analysis to facilitate more effective statistical analyses. For each case, the autopsy request and autopsy report were reviewed and data on the age, sex, cause of death, and medical history of the deceased were extracted.

1. Sampling

The femur head, femur midshaft, and the first molar in mandible were collected from each body. For the femur head, the surface was removed using an electric saw and the femur was cut at the neck to extract the spongy bone (Fig. 5). For the femur midshaft, the bone was cut with a saw and the surface of the bone and lumen were removed using a knife, to obtain the compact bone. For the first molar in mandible, the tooth was cut into 0.3 cm thick slices with a linear precision saw (Fig. 6) and the dentin was collected using a scalpel.

Figure 5. Sampling of femur.

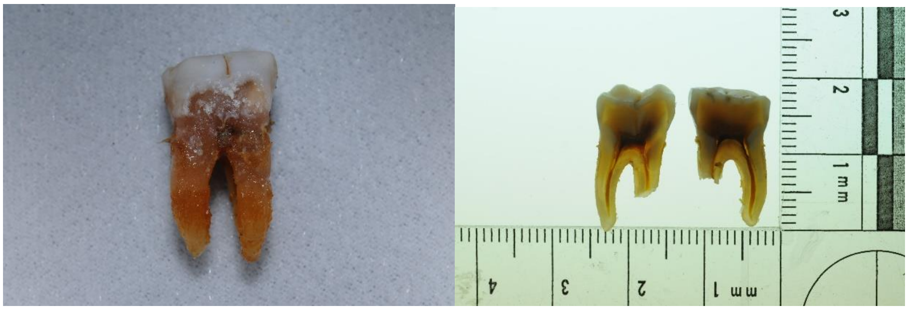

Figure 6. Sampling of teeth.

2. Pretreatment and collagen extraction

Bone samples were treated using the collagen-extraction method.[26,27] To eliminate possible contamination, the bone's surface was removed with 0.5M HCl solution, it was rinsed by deionized water, and dried in an oven. Dried bone samples were powdered into 1–2 mm particles using a mortar agate. Bone powder (600 mg) was treated using an acid-base-acid method using 0.5M HCl solution and 0.1M NaOH solution for 1 hr each step. Bone samples were then gelatinized by heating at 70℃ for 12 hr in a pH 3 solution. The gelatin solution was filtered using a 2.7-μm fiber filter to remove the remaining particles and then separated into two parts (molecular weight < 30,000 dalton [30kD] and > 30kD) using a Centriprep (Merck Millipore Co.). Solution with molecular weights above 30kD were dried by a freeze dryer.

Dentin samples were ground into 1–2mm powder and treated using the acid-base-acid method as the bone samples.

3. Reduction

Each sample was combusted at 900℃ in an elemental analyzer with an oxygen atmosphere to convert it to CO_2 gas. CO_2 samples were collected in the cryogenic traps of a 24-fold automatic reduction system connected to the elemental analyzer. After several iterations of cryogenic purification, CO_2 samples were reduced to graphite with hydrogen and Fe catalyst at 600℃ using the automatic reduction system.[28] Graphite sizes were set to 1mg, and the typical reduction time was 160 min. The typical reduction yield of all the samples was 95%. Graphite samples were measured for ^{14}C with an 1MV accelerator mass spectrometer (AMS) at Korea Institute of Geoscience and Mineral Resources (KIGAM).

4. Calibration of carbon age

To determine the year, the obtained ^{14}C content is calibrated to the calendar year. For calibration curve data, IntCal13 was used for samples calibrated to periods prior to 1950, and Bomb13NH2 for samples after 1950.[29-31] For the analysis program, OxCal4.3 was used. A 95.4% confidence limit (2σ) was obtained for the calendar year range. The calibration curve and analysis program, ‘Cheese burger’ developed by KIGAM was used for the cases where the result of calibration by using Bomb13NH2 showed the result after 2010 and had limitation in accurate year estimation.

5. Data processing for the calculation of estimation formula

Two estimated years (<1963 and >1963) were given for each sample. The femur head year and femur midshaft year were compared. If the femur head year was larger than the midshaft year, the femur head result was selected. For tooth samples, results within 10 years from the birth year were selected. Results before 1950 were excluded from the analysis.

Because the analysis programs (Oxcal and Cheese burger) provide estimated years as a range, the median of the range was used as a representative value for statistical processing.

Estimation formulas were developed through this process, using the selected result.

6. Statistical analysis

The mean and standard deviation of the difference between the actual birth year and the estimated birth year (ascertained from the tooth sample), and the difference between the actual death year and the estimated death year (ascertained through the femur samples) were determined. Two sample t-test was used for analysis of sex and Pearson correlation coefficient (Pearson's r) was used for age. Based on the above results, the formulas for estimating the birth year and death year were developed using multivariate analysis. The formulas were then evaluated for usefulness by adjusted R-square and root mean squared error (MSE). Statistical analyses were performed using IBM SPSS version 25.

III. RESULTS

Twenty-four autopsy cases were included for the analysis. Twenty cases (Case No. 1 - 20) were autopsy cases in 2015, and four (Case No. 21 - 24) from a 2014 publication were included for analysis. Deceased's demographic characteristics, cause of death, degree of decomposition and types of samples collected are presented in Table 2. The mean age was 50.0 years (ranging from 16 to 87 years). Sixteen were men and eight women. Birth years ranged from 1928 to 1999, and death years ranged from 1951 to 2015. Sixteen died in 2015. The causes of death were multiple injuries (n=9), ligature strangulation (n=5), hanging (n=4), sudden cardiac death (n=1), and unknown (n=5). The degree of decomposition of the bodies were skeletonization (n=7), partial skeletonization (n=7), and without decomposition (n=10). Femur head samples were collected from 20 cases, femur midshaft samples were collected from 23 cases, and tooth samples (first molar of mandible) were collected from 12 cases. The results of ^{14}C analysis and subsequent dating estimations are shown in Table 3. In Cases 5, 8, 9, 12, 15, 16, 17 and 18, the results of the femur estimated by Bomb13NH2 and Oxcal program were after 2010 or included after 2010, and so the results estimated by the ‘Cheese burger’ program of KIGAM were used for the analysis.

Table 2. Basic information of cases

No	Age	Sex	Birth year	Death year	Residence	COD	Decomposition degree	Femur head	Femur midshaft	Tooth
1	29	Male	1981	2011	Busan	Ligature strangulation	Complete skeletonization	O	O	O
2	50	Male	1960	2010	Busan	Ligature strangulation	Complete skeletonization	O	O	O
3	65	Male	1901	1966	Yangpyeong	Unknown	Complete skeletonization	O	O	X
4	51	Female	1900	1951	Yangpyeong	Unknown	Complete skeletonization	O	O	O
5	87	Female	1928	2015	Wonju	Multiple injuries due to traffic accident	Fresh	O	O	X
6	43	Male	1972	2015	Gimpo	Multiple injuries due to fall	Fresh	O	O	O
7	53	Female	1962	2015	Ansan	Unknown (Natural disease)	Partial skeletonization	O	O	O
8	49	Male	1966	2015	Incheon	Hanging	Partial skeletonization	O	O	X
9	54	Male	1961	2015	Incheon	Hanging	Partial skeletonization	O	O	O
10	73	Male	1942	2015	Chungju	Unknown (Natural disease)	Partial skeletonization	O	O	X
11	57	Male	1958	2015	Yeongwol	Multiple injuries due to traffic accident	Fresh	O	O	X
12	16	Male	1999	2015	Wonju	Multiple injuries due to traffic accident	Fresh	O	O	O
13	43	Male	1972	2015	Donghae	Unknown (CO intoxication)	Partial skeletonization	O	O	X
14	47	Female	1968	2015	Chuncheon	Multiple injuries due to fall	Fresh	O	O	X
15	87	Female	1928	2015	Yongin	Multiple injuries due to traffic accident	Fresh	O	O	X
16	24	Male	1990	2015	Chungju	Hanging	Partial skeletonization	O	O	O
17	56	Male	1958	2015	Eumseong	Multiple injuries due to traffic accident	Fresh	O	O	O
18	22	Male	1993	2015	Yangpyeong	Multiple injuries due to traffic accident	Fresh	O	O	O
19	58	Male	1957	2015	Gangneung	Multiple injuries due to fall	Fresh	O	O	O
20	59	Male	1956	2015	Gunpo	Hanging	Partial skeletonization	O	O	O
21	20	Female	1987	2007	Suwon	Ligature strangulation	Complete skeletonization	X	O	X
22	45	Female	1961	2006	Hwaseong	Ligature strangulation	Complete skeletonization	X	O	X
23	50	Female	1957	2007	Hwaseong	Ligature strangulation	Complete skeletonization	X	O	X
24	61	Male	1953	2014	Cheonan	Sudden cardiac death	Fresh	X	X	O

COD, cause of death

Table 3. Results of radiocarbon analysis

No	Age	Sex	Birth year	Death year	Sample	BP year	pMC(%)	2σ Calender year range (AD)
1	29	Male	1981	2011	Femur head	-590 ± 40	107.65 ± 0.51	1957~1958(7.4%) or 2001~2005(88.0%)
					Femur midshaft	-780 ± 40	110.23 ± 0.52	1957~1958(4.0%) or 1996~2000(91.4%)
					Tooth	-1360 ± 40	118.38 ± 0.56	1958~1959(7.0%) or 1985~1989(88.4%)
2	50	Male	1960	2010	Femur head	-1040 ± 40	113.81 ± 0.52	1958~1958(4.7%) or 1990~1994(90.7%)
					Femur midshaft	-2030 ± 40	128.70 ± 0.57	1961~1962(18.0%) or 1979~1980(77.4%)
					Tooth	-3390 ± 30	152.58 ± 0.65	1963~1963(2.0%) or 1968~1972(93.4%)
3	65	Male	1901	1966	Femur head	-1290 ± 40	117.46 ± 0.54	1958~1959(6.8%) or 1986~1990(88.6%)
					Femur midshaft	120 ± 40	98.47 ± 0.46	1675~1778(36.1%) or 1799~1942(59.3%)
4	51	Female	1900	1951	Femur head	210 ± 40	97.46 ± 0.50	1530~1540(0.6%), 1635~1697(28.5%), 1725~1815(46.2%), 1836~1877(2.9%) or 1917~(17.1%)
					Femur midshaft	120 ± 40	98.57 ± 0.47	1675~1778(36.1%) or 1799~1942(59.3%)
					Tooth	120 ± 40	98.48 ± 0.45	1675~1778(36.1%) or 1799~1942(59.3%)
5	87	Female	1928	2015	Femur head	-440 ± 40	105.60 ± 0.48	1956(37.7%) or 2002~2008 (57.7%)*
					Femur midshaft	-660 ± 40	108.62 ± 0.50	1956~1957(47.2%) or 1998~2001 (48.2%)*
6	43	Male	1972	2015	Femur head	-700 ± 40	109.16 ± 0.49	1957~1958(6.8%) or 1998~2002(88.7%)
					Femur midshaft	-1230 ± 40	116.51 ± 0.51	1958~1959(7.2%) or 1988~1990(88.2%)
					Tooth	-2500 ± 30	136.56 ± 0.59	1962~1962(12.3%) or 1974~1976(83.1%)
7	53	Female	1962	2015	Femur head	-690 ± 40	108.92 ± 0.49	1957~1958(7.1%) or 1998~2003(88.3%)
					Femur midshaft	-1210 ± 40	116.24 ± 0.54	1958~1959(7.8%) or 1988~1991(87.6%)
					Tooth	-3330 ± 30	151.41 ± 0.62	1963~1963(0.7%) or 1968~1972(94.7%)
8	49	Male	1966	2015	Femur head	-410 ± 40	105.20 ± 0.49	1956(37.7%) or 2003~2010 (57.7%)*
					Femur midshaft	-1250 ± 40	116.78 ± 0.52	1958(42.3%) or 1987~1990 (53.1%)*
9	54	Male	1961	2015	Femur head	-460 ± 40	105.95 ± 0.49	1956(35.0%) or 2002~2006 (59.9%) or 2008(0.5%)*
					Femur midshaft	-940 ± 40	112.35 ± 0.52	1957~1958(45.0%) or 1993~1996 (50.4%)*
					Tooth	-3430 ± 30	153.35 ± 0.61	1963~1963(1.8%), 1968~1970(89.6%) or 1971~1971(4.0%)
10	73	Male	1942	2015	Femur head	-630 ± 40	108.20 ± 0.50	1957~1958(7.2%) or 2000~2004(88.1%)
					Femur midshaft	-950 ± 40	112.49 ± 0.52	1957~1958(5.4%) or 1992~1996(90.0%)
11	57	Male	1958	2015	Femur head	-770 ± 40	110.01 ± 0.52	1957~1958(4.6%) or 1996~2001(90.8%)
					Femur midshaft	-1290 ± 40	117.35 ± 0.54	1958~1959(6.8%) or 1986~1990(88.5%)
12	16	Male	1999	2015	Femur head	-180 ± 40	102.31 ± 0.49	1955~1956(39.9%) or 2012~2015 (55.5%)*
					Femur midshaft	-240 ± 40	103.03 ± 0.47	1955~1956(44.3%) or 2009~2013(50.1%) or 2015(1.0%)*
					Tooth	-540 ± 40	107.01 ± 0.48	1957~1957(8.3%), 2002~2007(86.3%) or 2008~2008(0.9%)

13	43	Male	1972	2015	Femur head	-660 ± 30	108.51 ± 0.44	1957~1958(7.0%) or 2000~2003(88.4%)
					Femur midshaft	-1040 ± 30	113.76 ± 0.45	1958~1958(4.9%) or 1990~1994(90.5%)
14	47	Female	1968	2015	Femur head	-810 ± 30	110.67 ± 0.42	1957~1958(2.4%) or 1995~1999(93.0%)
					Femur midshaft	-790 ± 30	110.39 ± 0.42	1957~1958(3.2%) or 1996~2000(92.2%)
15	87	Female	1928	2015	Femur head	-450 ± 30	105.70 ± 0.41	1956(37.6%) or 2002~2006 (56.2%) or 2008 (1.6%)*
					Femur midshaft	-530 ± 30	106.79 ± 0.40	1956(39.1%) or 2001~2005 (56.3%)*
16	24	Male	1990	2015	Femur head	-290 ± 30	103.73 ± 0.42	1955~1956(36.7%) or 2007~2012 (58.7%)*
					Femur midshaft	-480 ± 30	106.13 ± 0.42	1956(32.9%) or 2002~2005 (62.5%)*
					Tooth	-840 ± 30	110.96 ± 0.40	1957-1958(3.9%) or 1995~1999(91.5%)
17	56	Male	1958	2015	Femur head	-420 ± 30	105.35 ± 0.43	1956(39.8%) or 2003~2008 (55.6%)*
					Femur midshaft	-960 ± 30	112.73 ± 0.45	1957~1958(45.3%) or 1992~1995 (50.1%)*
					Tooth	-2030 ± 40	128.81 ± 0.58	1961~1962(18.0%) or 1979~1980(77.4%)
18	22	Male	1993	2015	Femur head	-400 ± 30	105.05 ± 0.40	1956(37.0%) or 2003 (0.4%) or 2005~2010 (58.0%)*
					Femur midshaft	-440 ± 30	105.69 ± 0.40	1956(37.9%) or 2002~2006 (56.0%) or 2008 (1.5%)*
					Tooth	-710 ± 30	109.22 ± 0.43	1957~1958(6.6%) or 1998~2002(88.8%)
19	58	Male	1957	2015	Femur head	-700 ± 30	109.07 ± 0.42	1957~1958(6.6%) or 1999~2002(88.8%)
					Femur midshaft	-1700 ± 30	123.62 ± 0.48	1959~1960(38.2%), 1961(7.9%) or 1982~1983(49.3%)
					Tooth	-3170 ± 30	148.42 ± 0.57	1962~1963(10.9%) or 1970~1973(84.5%)
20	59	Male	1956	2015	Femur head	-910 ± 30	112.00 ± 0.43	1957~1958(5.2%) or 1993~1997(90.2%)
					Femur midshaft	-2650 ± 30	139.05 ± 0.53	1962(13.0%), 1973(2.7%) or 1974~1975(79.7%)
					Tooth	-940 ± 30	112.41 ± 0.44	1957~1958(4.7%) or 1993~1996(90.7%)
21	20	Female	1987	2007	Femur midshaft	-690 ± 30	108.93 ± 0.43	1957~1958(6.9%) or 1999~2002(88.6%)
22	45	Female	1961	2006	Femur midshaft	-2090 ± 30	129.77 ± 0.49	1962(11.0%) or 1978~1979(84.4%)
23	50	Female	1957	2007	Femur midshaft	-1760 ± 30	124.46 ± 0.49	1959~1960(22.5%), 1961~1962(6.8%) or 1981~1983(66.2%)
24	61	Male	1953	2014	Tooth	-560 ± 30	107.18 ± 0.39	1957(7.7%) or 2002~2006(87.7%)

BP, Before present; pMC, percent modern carbon

* Calender year range was estimated by Cheese burger program of KIGAM.

1. Results of femur analysis

The results from the femur head sample and the femur midshaft sample were compared. If the percent modern carbon (pMC) of the femur head was greater than that of the femur midshaft, results before 1963 were adopted, and if pMC of the femur head was smaller than that of the femur midshaft, results after 1963 were adopted. Therefore, of the two results, the femur head results closer to the death year than that of the femur midshaft was selected for analysis. Because the selected results were presented as a range, the median of the range was designated as the femur head year and the femur midshaft year was used for statistical analysis.

The results of Case 3 the femur midshaft sample and Case 4 femur head and femur midshaft samples were before 1950 and were thus excluded from the development of the death year formula. Case 14 was excluded from analysis because the result of the femur midshaft was closer to the death year than that of the femur head. The selected results for femur samples are shown in Table 4.

Table 4. Data processing for death year estimation

No	Age	Sex	Death year	pMC FH(%)	FH year range	FH year	pMC FS(%)	FS year range	FS year
1	29	Male	2011	107.65 ± 0.51	2001-2005	2003	110.23 ± 0.52	1996-2000	1998
2	50	Male	2010	113.81 ± 0.52	1990-1994	1992	128.70 ± 0.57	1979-1989	1984
3	65	Male	1966	117.46 ± 0.54	1958-1959	1958.5			
5	87	Female	2015	105.60 ± 0.48	2002-2008	2005	108.62 ± 0.50	1998-2001	1999.5
6	43	Male	2015	109.16 ± 0.49	1998-2002	2000	116.51 ± 0.51	1988-1990	1989
7	53	Female	2015	108.92 ± 0.49	1998-2003	2000.5	116.24 ± 0.54	1988-1991	1989.5
8	49	Male	2015	105.20 ± 0.49	2003-2010	2006.5	116.78 ± 0.52	1987-1990	1988.5
9	54	Male	2015	105.95 ± 0.49	2002-2006, 2008	2005	112.35 ± 0.52	1993-1996	1994.5
10	73	Male	2015	108.20 ± 0.50	2000-2004	2002	112.49 ± 0.52	1992-1996	1994
11	57	Male	2015	110.01 ± 0.52	1996-2001	1998.5	117.35 ± 0.54	1986-1990	1988
12	16	Male	2015	102.31 ± 0.49	2012-2015	2013.5	103.03 ± 0.47	2009-2013, 2015	2012
13	43	Male	2015	108.51 ± 0.44	2000-2003	2001.5	113.76 ± 0.45	1990-1994	1992
15	87	Female	2015	105.70 ± 0.41	2002-2006, 2008	2005	106.79 ± 0.40	2001-2005	2003
16	24	Male	2015	103.73 ± 0.42	2007-2012	2009.5	106.13 ± 0.42	2002-2005	2003.5
17	56	Male	2015	105.35 ± 0.43	2003-2008	2005.5	112.73 ± 0.45	1992-1995	1993.5
18	22	Male	2015	105.05 ± 0.40	2003-2010	2006.5	105.69 ± 0.40	2002-1008	2005
19	58	Male	2015	109.07 ± 0.42	1999-2002	2000.5	123.62 ± 0.48	1982-1983	1982.5
20	59	Male	2015	112.00 ± 0.43	1993-1997	1995	139.05 ± 0.53	1973-1975	1974
21	20	Female	2007				108.93 ± 0.43	1999-2002	2000.5
22	45	Female	2006				129.77 ± 0.49	1978-1979	1978.5
23	50	Female	2007				124.46 ± 0.49	1981-1983	1982

pMC, percent moedern carbon; FH, femur head;FS, femur midshaft

2. Results of tooth analysis

For tooth samples, a result less than 10 years from the actual birth year was adopted. Case 2, 7, and 9 were excluded because both results were within 10 years, so it was difficult to select one of them. Analysis of the results of the selected tooth samples are shown in Table 5.

Table 5. Data processing for birth year estimation

No	Age	Sex	Birth year	pMC Tooth	Tooth year range	Tooth year
1	29	Male	1981	118.38 ± 0.56	1985-1989	1987
6	43	Male	1972	136.56 ± 0.59	1974-1976	1975
12	16	Male	1999	107.01 ± 0.48	2002-2008	2005
16	24	Male	1990	110.96 ± 0.40	1995-1999	1997
17	56	Male	1958	128.81 ± 0.58	1961-1962	1961.5
18	22	Male	1993	109.22 ± 0.43	1998-2002	2000
19	58	Male	1957	148.42 ± 0.57	1962-1963	1962.5
20	59	Male	1956	112.41 ± 0.44	1957-1958	1957.5
24	61	Male	1953	107.18 ± 0.39	1957	1957

pMC, percent modern carbon

3. Analysis for variables

Factors affecting differences between tooth year and birth year, differences between death year and femur head year, differences between death and femur midshaft year, and differences between femur head year and femur midshaft year were analyzed. Their averages, standard deviations, and ranges are presented in Table 6.

Table 6. Descriptive statistics of differences between estimation year and actual year

	No. of subjects	Mean (±SD)	Median (IQR)	Range
Tooth-Birth	9	4.8 (±1.9)	5.5 (3.3)	1.5-7.0
Death-FH	18	11.3 (±4.7)	10.0 (6.3)	1.5-20.0
Death-FS	20	20.7 (±9.3)	22.3 (14.1)	3.0-41.0
FH-FS	17	9.4 (±5.7)	9.5 (6.3)	1.5-21.0

FH, femur head;FS, femur midshaft;SD, Standard deviation; IQR, Interquartile range

For age variant, there was a statistically significant negative correlation between age and the difference between tooth year and birth year. The remaining did not show statistically significant results. However, as a result of analyzing only the male cases, there was a statistically significant positive correlation in all differences. Difference between tooth year and birth year could not analyzed because there were no female cases (Table 7).

For the difference in tooth year and birth year, all cases were male, so the effect of sex variant could not be analyzed. For the remaining differences, sex variant had no effect. Analysis of only those ages 40 and older showed that all differences tended to be greater in male than in female, although there were no statistical significances (Table 7).

The cause of death and the degree of decomposition were not found to affect the differences.

Table 7. Analysis on the influence of age and sex

		Tooth-Birth			Death-FH			Death-FS			FH-FS		
		No	Pearson's r	p-value	No	Pearson's r	p-value	No	Pearson's r	p-value	No	Pearson's r	p-value
Age		9	-0.75	0.020	18	0.385	0.115	20	0.415	0.069	17	0.217	0.404
Age (only male)					15	0.589	0.021	14	0.771	0.001	14	0.677	0.008
		No	Mean (±SD)	p-value	No	Mean (±SD)	p-value	No	Mean (±SD)	p-value	No	Mean (±SD)	p-value
Sex	Male	9	4.8 (±1.9)	·	15	11.3 (±5.0)	0.948	14	21.6 (±9.8)	0.533	14	10.0 (±5.9)	0.304
	Female	0	·		3	11.5 (±2.6)		6	18.7 (±8.6)		3	6.2 (±4.5)	
Sex (>40)	Male	5	3.5 (±1.5)	·	11	13.3 (±4.0)	0.492	10	26.5 (±6.2)	0.150	10	12.7 (±4.6)	0.056
	Female	0	·		3	11.5 (±2.6)		5	21.1 (±6.9)		3	6.1 (±4.5)	

FH, femur head;FS, femur midshaft;SD, Standard deviation

P-values for age were determined with use of Pearson correlation.

P-values for sex were determined with use of the two sample t-test.

4. Formula and evaluation

Based on the above, formulas were obtained and evaluated.

A. Birth year estimation formula using tooth year

For the birth year estimation formula, three candidates were compared: formula 1 (multiple linear regression analysis using age and tooth year as independent variables), formula 2 (simple linear regression analysis using only tooth year as an independent variable), and formula 3 (tooth year minus the mean of difference between tooth year and birth year). The statistical information on the formulas is presented in Table 8.

Formula 1: Birth year = 0.631x(Tooth year)-0.313x(Age)+737.081
Formula 2: Birth year = 0.923x(Tooth year)+147.431
Formula 3: Birth year = (Tooth year)-4.8

The adjusted R-square value was up to 0.995 in both formula 1 and formula 2. However, in formula 1, the p-value for the age variable was not significant (0.255) and variance inflation factor (VIF) was 10 or more. In formula 2, the root mean squared error (MSE) value for internal validation was smaller than the other formulas. Thus, formula 2 was determined to be superior to formulas 1 and 3.

B. Death year estimation formula using femur head year

Four candidate death year estimation formulas were compared: formula 1 (multiple linear regression analysis using sex, age, and femur head year as independent variables); formula 2 (multiple linear regression analysis using age, and femur head year as independent variables); formula 3 (simple linear regression analysis using only femur head year as an independent variable); and formula 4 (femur head year plus the mean of difference between death year and femur head year). Statistical information on the formulas is presented in Table 8.

Formula 1: Death year = 0.989x(Femur head year)+0.123x(age)–3.329x(sex)+30.982
(Male=1, Female=2)
Formula 2: Death year = 0.954x(Femur head year))+0.081x(age)+98.585
Formula 3: Death year = 0.912x(Femur head year)+186.784
Formula 4: Death year = (Femur head year)+11.3

The adjusted R-square value of formula 2 was slightly higher compared to formula 1; but in formula 1, the root MSE value for internal validation was smaller than the other formulas. Thus formula 1 was determined to be superior to other formulas.

Table 8. Estimation formulas by multivariate analysis and evlauation of their usefulness

	Variables	β	p-value	VIF	R-square	Adjusted R-square	Root MSE
Birth year formula 1	Constant	737.081	0.168		0.996	0.995	1.28
	Age	-0.313	0.255	108.562			
	Tooth year	0.631	0.035	108.562			
Birth year formula 2	Constant	147.431	0.015		0.996	0.996	1.13
	Tooth year	0.923	<0.001	1.000			
Birth year formula 3							1.81
Death year formula 1	Constant	30.982	0.888		0.870	0.842	4.03
	Sex	-3.329	0.388	1.665			
	Age	0.123	0.120	1.801			
	Femur head year	0.989	<0.001	1.263			
Death year formula 2	Constant	98.585	0.629		0.863	0.844	4.19
	Age	0.081	0.178	1.098			
	Femur head year	0.954	<0.001	1.098			
Death year formula 3	Constant	186.784	0.354		0.844	0.835	4.45
	Femur head year	0.912	<0.001	1.000			
Death year formula 4							4.52

VIF,variance inflation factor;MSE, mean squared error

IV. DISCUSSION

Radiocarbon dating has been made possible thanks to nuclear tests that have been carried out since the 1950s. The rapidly increased concentration of radiocarbon in the atmosphere has been used for forensic purposes. For deaths before 1950 the accuracy of dating is limited. However, if a death is determined to have occurred before 1950, the information may still be useful in that it aids in the prioritizing of cases for investigation. The general criterion for determining whether it is after 1950 is when the pMC is greater than 100%. Actually, by 1954, the pMC value is less than 100%, which is not clearly distinguished from the results before 1950. Thus, it should be noted that if a death occurred near 1954, there is a potential that results may incorrectly indicate that the death occurred before 1950. In this study, there were a total of 2 cases in which the results were reported before 1950. Case 3 was born in 1901 and died in 1966. The results of the femur head were after 1950, but the results of the femur midshaft were before 1950 and the femur midshaft year could not be determined. In this case, however, when one of two results of the femur head (1958 ~ 1959 and 1986 ~ 1990) had to be selected, the fact that the results of the femur midshaft were earlier than 1950, helped the choice of 1958 ~ 1959, and as a result, the results of the femur midshaft helped to date. Case 4 was born in 1900 and died in 1951, and the results of tooth, femur head and femur midshaft were all before 1950. In this case, the actual death year was 1951, but it could not be estimated from the analysis results that the actual death year is after 1950. This is an example showing that the actual death could be after 1950 even if the femur head results were before 1950. Further studies are needed in cases where the actual death year is after 1950 and radiocarbon analysis is inaccurate.

If the analysis result is after 2010, the current OxCal calibration program cannot be used to estimate the exact year. For example, in case 12, only one result before 1963 from this program was provided, and result after 1963 was not provided. However, if the femur head and femur midshaft results are compared, it is possible to predict that the results are actually after 2010. This problem may be solved when the program is upgraded (Intercal 2019 data will be provided soon), and then data up to 2015 will be able to be analyzed. In this study KIGAM's calibration program, which can estimate the results after 2010, was used for these cases.

Previous studies have estimated birth year of birth using tooth enamel.[14,32,33] Enamel is a good material for dating because, after being generated early in the development of the tooth, it remains unchanged until death, and it is a solid and stable material of which 96% of components are mineral. However, because it is located on the surface of the tooth, it is easy to be affected by the external environment. Moreover, analysis of enamel is difficult because the proportion of enamel volume is small and the amount of organic matter needed for analysis is also small. By contrast, dentin is produced later than enamel, but it is protected from the external environment by surrounding enamel and cementum. Moreover, the dentin volume of the tooth is larger than that of enamel and its ratio of organic matter is higher, which makes it easy to analyze. Considering these points, this study performed analysis using dentin and developed the formula using the subsequent results. The most significant research on the estimation of birth year using teeth is the study of Spalding et al.[14], which collected and analyzed 33 tooth samples, including several types of teeth, from 22 cases. The results were corrected to the time of enamel production in each tooth-type. As a result, the average and standard deviation of the difference between the estimated year and the actual year were 1.6 years and 2.1 years, respectively. For comparison, the data of the current study was processed in the same way as the study of Spalding et al., and the results were compared (Table 13). The mean was 6.66 years and the standard deviation was 1.72 years. Because the data was corrected at the end of dentin generation, the difference between the estimated and actual years increased. Dentin generation occurs over a longer time than enamel, so the correction method used in the previous study was not suitable for the current study which used dentin. Although the number of cases between the previous study and the current study are different, standard deviation was less in the current study. This indicates that analysis using dentin is not at least inferior to analysis using enamel. Dentin is a suitable sample material for radiocarbon dating experiments because of its high percentage of teeth volume and high organic content. It is especially useful in the forensic field when repeated measurements are required for verification.

Table 9. Tooth analysis results corrected for comparison with previous studies

No	Sex	Age	Dentin formation time	pMC Tooth	Range of tooth year	Tooth year	Actual DOB	14C estimated DOB	Difference 1	Difference 2
1	Male	29	11.5	118.38 ± 0.56	1985.78 ~ 1989.22	1987.50	1981.90	1976.00	5.60	5.90
6	Male	43	11.5	136.56 ± 0.59	1974.82 ~ 1976.90	1975.86	1972.73	1964.36	3.13	8.37
12	Male	16	11.5	107.01 ± 0.48	2002.18 ~ 2008.78	2005.48	1999.58	1993.98	5.90	5.60
16	Male	24	11.5	110.96 ± 0.40	1995.50 ~ 1999.06	1997.28	1990.78	1985.78	6.50	5.00
17	Male	56	11.5	128.81 ± 0.58	1961.92 ~ 1962.42	1962.17	1958.86	1950.67	3.31	8.19
18	Male	22	11.5	109.22 ± 0.43	1998.24 ~ 2002.66	2000.45	1993.18	1988.95	7.27	4.23
19	Male	58	11.5	148.42 ± 0.57	1962.96 ~ 1963.26	1963.11	1957.61	1951.61	5.50	6.00
20	Male	59	11.5	112.41 ± 0.44	1957.94 ~ 1958.60	1958.27	1956.11	1946.77	2.16	9.34
24	Male	61	11.5	107.18 ± 0.39	1957.20 ~ 1957.88	1957.54	1953.35	1946.04	4.19	7.31
Mean									4.84	6.66
SD									1.72	1.72

pMC, percent mordern carbon; DOB, date of birth; SD, standard deviation

Difference 1 = Tooth year - Actual DOB

Difference 2 = Actual DOB - 14C estimated DOB

In this study, the results of tooth analysis show that the difference between tooth year and birth year is negatively correlated with age. However, this may be due to the characteristics of the bomb peak curve rather than an actual negative correlation. In cases born near 1963, the difference between tooth year and birth year decreases due to the characteristic of the bomb peak curve which decreases with increasing pMC value in the affected period. Compared to the case where the pMC increases or decreases constantly during tooth creation, when pMC increases and then decreases (or vice versa) during that period, the difference decreases between the pMC value at birth and the pMC value of the tooth as a result of accumulation of pMC changes during the tooth development period. At the time of study, elderly cases were born near 1963 and the younger cases were born when the pMC value was continuing to decrease.

Teeth of twelve cases were examined in this study, but three were not used for the development of the estimation formulas. This is because there were no clear criteria for which of the two results obtained from these cases should be selected. In this study, the selection criterion of the tooth results was that the estimated birth year was within 10 years of the actual birth year. This was because the growth of the first molar of the mandible progresses until 9-10 years old. In three excluded cases, both results met this criterion. This problem can occur frequently when the estimated birth year is near 1963, which is the peak of the bomb peak curve. It is expected to be frequently encountered in the field, even when applying analysis using tooth samples. In practice, when the birth year is estimated using results of tooth analysis, the death year estimated through analysis of the femur and the age estimated by forensic odontological examination is used to select the tooth year. However, if two results which are close to 1963 are given, there is no clear standard for which to choose. For example, if the death year by femur analysis is 1990, the age estimated is the mid-20s, and the tooth year is 1963 and 1968-1970, it is difficult to determine which one to choose. This problem may be solved by comparing the results of enamel on the same tooth or by analyzing the dentin of other teeth that are developed later than the first molar in mandible.

This study has limitation of small sample size which lowers the reliability of the birth year estimation formula. The accuracy of the formula may be improved if the equations are further developed by dividing the cases into those where the pMC increases or decreases continuously or increases and decreases during tooth generation. Despite this limitation, this study is significant because the dentin of tooth samples was analyzed instead of enamel, and only the first molars in the mandible were analyzed, to reduce the error of each tooth.

Estimation of the death year through analysis of the femur is based on the premise that femur head year is closer to the death year since the femur head is spongy bone which has a higher turnover rate than the compact bone of the femur midshaft. In this study femur head and femur midshaft were analyzed together, for twenty cases. Of these, 18 cases delivered results congruent with this assumption. One exceptional case delivered results before 1950. Results of the other exceptional case (Case 14) indicated that the femur midshaft year was closer to the death year than the femur head year. If this anomaly had occurred at a higher rate, it would indicate that needs to be reconsidered in estimating death years through radiocarbon isotope analysis. Possible reasons for this anomaly include human error (that the specimen was reversed during the experiment or contaminated during the pretreatment process), that the deceased had a bone metabolism disease, or that the bomb peak curve at that period had a special pattern which influenced the results, but no clear conclusions were made. However, in this instance the pMC of the femoral head was 110.67 ± 0.42%, and the pMC of femur midshaft was 110.39 ± 0.42%. Considering the range of error, the pMC of the femur head may actually be larger than that of the femur midshaft (i.e. the femur head year is closer to the death year) which may also explain the results.

An estimation formula of death year using the femur head was difficult to develop compared with the estimation of birth year using the tooth year. The difference between the femur head year and the death year is large, so there is more room for error. Moreover, consideration should be given to age and sex variables. As confirmed by the Ubelaker study,[34] as the age increases, the turnover rate of the bone decreases and the difference between the death year and the femur head year increases. Females are expected to show different turnover rates than men of the same age due to the effects of estrogen, and in particular, it is expected to show different patterns according to periods (childhood, childbearing age and menopause). So, age and sex variables should be reflected in the estimation formula. In this study, it was confirmed that age affects turnover rate in male, but it did not show any difference according to age in female and sex. This is thought to be due to the lack of the number of cases, and especially, the lack of cases of young female limited the statistical analysis. Nevertheless, the estimation formula obtained in this study reflect the age and sex variables, and consequently the adjusted R-square was 0.842, thus it needs to be supplemented for practical application. In future studies, it is advised to include more cases and develop an estimation formula by age and sex.

Despite these limitations, this is the largest number of cases to be analyzed as a single study for the death year estimation to date. In particular, to reduce the error, only the femur was analyzed. It will be necessary to develop and validate a dating estimation formula using other bones in case of the absence of a femur sample. Also, there is need to compare the femur with other parts of the skeleton.

One of the main objectives of this study was to find an estimation formula that could be applied to practice. There were errors that could be caused during data processing. The first is error due to monthly differences. Even in the same year, the difference between January and December is actually one year. In this study, information on birth year and death year as well as birth date and death date for each case were collected. However, the dates were not reflected in the estimation process. This is because in practice, no information about the date is available, so we determined it to be appropriate to process the data without the actual date. However, it should be considered that this may cause errors. Secondly, this study included mainly cases who died in 2015, and there is a limitation in the analysis using the bomb peak curve until 2009.[29] If the bomb peak curve is later updated, the estimation formula will probably be improved by supplementing the data. Thirdly, the possibility of error due to the geopolitical characteristics of the Korean peninsula must be considered. It is known that pMC values in the Far East differ from those of Bomb13NH2 in some years. And nuclear testing by North Korea may increase radiocarbon concentrations in the atmosphere of the Korean Peninsula. This issue may be solved by making a bomb peak curve using data measured in Korea in the future and developing the formula by using it. For reference, radiocarbon data of Korea are updated every year by analysis of the tree rings at KIGAM, and a calibration program for Korean radiocarbon data was developed.

This study is meaningful because it analyzes the largest number of samples on a single study scale and uses samples from only a specific site to increase the accuracy of the analysis. We anticipate further research will develop more accurate estimation formulas which can be applied in practice.

V. CONCLUSION

This study was aimed at estimating the birth and death year of human skeletal remains by using radiocarbon analysis, and increasing the accuracy of the analysis by sampling of dentin in the 1st molar in mandible, spongy bone of femur head, and compact bone of femur midshaft. Although the result is insufficient to be applied in practice, this study is meaningful because it analyzes the largest number of samples on a single study scale, uses samples from only a specific and identical skeleton to increase the accuracy of the analysis, and especially uses dentin for the birth year estimation.

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ABSTRACT(IN KOREAN)

방사성 탄소동위원소 분석을 이용한 백골화 골격의 연대추정

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박종필

법의학 분야에서 변사자의 신원확인은 중요한 업무 중 하나이다. 현재의 기술 수준으로 변사자의 신원확인을 위해 나이, 성별 및 키를 추정할 수 있다. 변사자에 대한 연대추정, 즉, 변사자의 출생연도 및 사망연도 추정은 아직까지는 실무에 적용하기에 제약이 있다. 최근 방사성 탄소동위원소 분석을 이용한 연대추정방법이 소개되면서 이를 인체에 적용해 보고자 하는 연구들이 진행되고 있다. 본 연구는 방사성 탄소동위원소 분석을 이용한 백골화 인체골격의 연대추정법의 유용성을 검토하고, 실무에 적용 가능한 출생연도 및 사망연도 추정식을 계발하는 것을 목적으로 하였다.

본 연구는 2015년 1월부터 12월까지 국립과학수사연구원에서 시행된 부검례 중 출생연도와 사망연도를 정확히 알 수 있는 20 증례를 대상으로 하였다. 그리고 기존 연구에서 보고된 4증례를 통계분석을 위해 포함시켰다. 각각의 증례에 대해 아래턱 첫번째 큰어금니, 대퇴골 머리부위 및 대퇴골 몸통부위를 채취하였고, 아래턱 첫번째 큰어금니 중 상아질, 대퇴골 머리부위 중 해면뼈 그리고 대퇴골 몸통부위 중 치밀뼈를 분리하였다. 각각에 대해

방사성 탄소동위원소 분석을 시행한 후 Bomb peak 곡선을 이용하여 추정연도를 구하였으며, 실제 출생연도 및 사망연도와 방사성 탄소동위원소 분석을 통해 추정된 연도 사이의 사이를 이용해 출생연도 및 사망연도 추정식을 만들어 그 유용성을 평가하였다.

연구결과 치아연도와 출생연도의 차이는 평균 4.8년이고, 사망연도와 대퇴골머리연도의 차이는 11.3년이었다. 남성인 경우 사망연도와 대퇴골머리연도 사이의 차이가 나이가 증가함에 따라 커지는 경향을 보였으나, 여성인 경우 나이의 증가의 영향 및 성별에 따른 차이에 대해서 본 연구에서는 확인할 수 없었다.

대퇴골에 대한 방사성 탄소 동위원소 분석을 통해 얻어진 사망연도 추정식은 낮은 설명력(R^2=0.842)을 보여 실무에 적용하기에는 부족하였다. 치아 분석을 통해 얻어진 출생연도 추정식은 상대적으로 높은 설명력(R^2=0.996)을 보였으나, Bomb peak 곡선의 구간에 따라 차이의 정도가 다름을 확인하였다.

결론적으로 시료수 부족으로 인해 정확한 출생연도 및 사망연도 추정식을 개발하는 데에는 한계가 있었지만, 현재까지 시행된 연구 중 가장 많은 시료를 분석한 연구로서 오차를 줄이기 위해 특정 부위만을 분석에 활용하였다는 점에서 의미있는 연구라고 할 수 있겠다.

핵심되는 말 : 방사성 탄소동위원소, 연대추정, 법의인류학, 치아, 대퇴골