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RESEARCH ARTICLE

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Changes in intracranial volume and cranial shape in modern Koreans over four decades

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Abstract

Objectives: This study investigated whether there was any secular change in cranial vault morphology among Koreans born between the 1930s and 1970s, a period of dramatic shift in Korea's socioeconomic conditions.

Materials and methods: Using three-dimensional MRI volumetry, we obtained the intracranial volume (ICV) and craniometric measurements of 115 healthy Koreans: 58 individuals (32 males and 26 females) born in the 1930s (1926–1936) and 57 (28 males and 29 females) born in the 1970s (1972–1979).

Results: The intracranial volume of males was 1502.3 ± 110.3 cm^3 for the 1930s group and 1594.1 ± 99.5 cm^3 for the 1970s group, and for females, it was 1336.0 ± 53.0 cm^3 for the 1930s group and 1425.9 ± 79.6 cm^3 for the 1970s group. On average, ICV increased by 94 cm^3 in males and by 90 cm^3 in females. Cranial measurements for the 1970s group were significantly larger than the 1930s group for both sexes except in female cranial length. Each measurement was significantly correlated with ICV [cranial height ($R = 0.720$), breadth ($R = 0.706$), and length ($R = 0.531$)]. The cephalic index decreased from 0.846 to 0.828 in males, indicating the cranium became narrower relative to the cranial length. In females, the cephalic index increased from 0.831 to 0.850. Sex and birthyear were marginally interrelated in cephalic indices.

Discussion: From the 1930s to 1970s, the Korean Peninsula experienced important historical shifts, and we speculate that the consequent shift in socioeconomic status is the most likely factor responsible for Koreans' cranial vault remodeling.

KEYWORDS
cephalic index, industrialization, MRI, plasticity, secular change

1 | INTRODUCTION

The concept of cranial plasticity has first arisen from Boas's immigrant study (1912), and many researchers have argued over the influence of genetic and/or environmental factor on the evolution of human cranial morphology (Gravlee, Bernard, & Leonard, 2003; Sparks and Jantz, 2002; Sparks and Jantz, 2003). Short-term changes over a few generations are primarily environmental, while longer-term changes likely involve both genetic and environmental components (Jantz and Meadows Jantz, 2000).

Numerous studies have been carried out to determine the secular changes in cranial morphology. The process of brachycephalization, increasing value of cranial or cephalic index, had been observed since the 14th century among European populations (Buretic-Tomljanovic et al., 2004; Rock, Sabieha, & Evans, 2006). Since the beginning of 21st century, the increase in cranial length has not been accompanied by increase in cranial breadth, known as debrachycephalization (Bodzsaŕ and Susanne, 1998; Gyenis, 1994). In Asian, increase in cranial length were accompanied by prominent increase in cranial breadth until 1990, soon followed by decrease in cephalic index (Koh et al., 2001; Kouchi, 2000; Min, 2012).

TABLE 1 Physical characteristics of subjects in two birth cohorts

	1930s		1970s	
	Men (*n* = 32)	Women (*n* = 26)	Men (*n* = 28)	Women (*n* = 29)
Ages (years)	68.4 ± 3.7	67.2 ± 3.1	24.3 ± 2.2	24.6 ± 2.0
Birth Year	1926–1936	1927–1938	1972–1980	1973–1979
Height (cm)	166.3 ± 5.1	157.4 ± 4.7	175.3 ± 3.8	162.1 ± 3.8
Weight (kg)	63.9 ± 6.5	57.6 ± 8.2	71.5 ± 10.3	52.3 ± 4.0
BMI (kg m^{-2})	23.1 ± 1.9	23.2 ± 2.8	23.2 ± 3.0	19.9 ± 1.4

mean ± SD.

As the shape of cranium changes, the cranial size changes accordingly. To estimate the cranial volume, researchers have traditionally used various filling materials to pack the interior of the skull (Sahin et al., 2007). With the advances in magnetic resonance imaging (MRI) as a fundamental tool for brain volumetric analysis, intracranial volume (ICV) has been routinely measured and used as a head size correction factor (Eritaia et al., 2000). Although skull thickness and size slightly changes throughout lifetime (Finby and Kraft, 1972; Lynnerup, 2001; Todd, 1924), it is known to be minimally affected by the aging process (Jantz and Meadows Jantz, 2000; Liu et al., 2003; Matsumae et al., 1996). In this study, we have used ICV and cephalic index to determine the cranial volume and shape.

The objective of the current study was to investigate any change in cranial size and morphology among the Korean populations born in 1930s and 1970s. Because it is known that environment affects early development of skull (Jantz and Meadows Jantz, 2000; Rushton and Osborne, 1995), we focused on Koreans born in 1930s who suffered from the period of Japanese colonization (1910–1945) and Korean War (1950–53) and Koreans born in 1970s who benefited from the substantial economic growth in the second half of the 20th century. Using MRI data, we measured the ICV of subjects from birth cohorts and obtained craniometric measurements and the cephalic index to describe any change in cranial shape that occurred along with size change.

2 | MATERIALS AND METHODS

2.1 | Subjects

In the 1970s group (birth year 1972–1979), 57 healthy Koreans including 28 men and 29 women were enrolled in the study. The age range of this group was between 20 and 28 years, with a mean age of 24.32 ± 2.21 years for men and 24.55 ± 1.95 years for women [$t(55) = -0.41$, $p = 0.67$]. Total of 58 Koreans including 32 men and 26 women were in the 1930s group (birth year 1926–1936). The age range was between 65 and 75, with a mean age of 68.37 ± 3.67 years for men and 67.15 ± 3.14 years for women [$t(56) = 1.34$, $p = 0.18$]). The participants were recruited through advertisements on the Korea University web page and in the local newspapers, and written informed consent was obtained from each individual before participation. The study was approved by the Institutional Review Board of the College of Medicine, Korea University. The researchers took the medical history of the participants and examined their neurologic functions to exclude any individuals with possible neurologic abnormalities. Height and weight were measured with a digital scale by nurses who do not take part in the study. Demographic data on the sample is found in Table 1.

2.2 | MRI acquisition

Participants underwent MRI on a 1.5-T Magnetom vision instrument (Siemens, manufactured in Erlangen, Germany) using T1-weighted magnetization prepared rapid acquisition gradient echo sequence, with the following parameters: repetition time = 9.7 ms, echo time = 4 ms, flip angle = 12°, slice thickness = continuous 1.5 mm, number of slices = 118, and matrix 256 × 256. The results were saved in a file in the DICOM (Digital Imaging and Communications in Medicine) format and imported into the V-work 3.5 software (Cybermed, Seoul, Korea) for processing.

2.3 | Volumetry

The intracranial volume was obtained on 1.5-mm sagittal MR slides by manually delineating margins of the inner side of crania and summing them up with V-work software version 3.5 (Cybermed, Korea), which has been used in previous studies (Koh et al., 2005; Park et al., 2006). Figure 1 shows how the instrument was standardized using anatomical landmarks and planes and then reconstructed three-dimensionally to measure the volume. The inferior boundary was defined by a plane parallel to the mammillary body-posterior commissure plane, which was aligned for the posterior rim of the foramen magnum, so the brainstem structures below were excluded (Luft et al., 1999). Two raters measured intracranial volume of each subject. Interrator reliability was evaluated with intracranial volume in 10 subjects of each group, and intraclass correlation coefficients (ICC) were over 0.95, suggesting that the segmentation method was reliable.

2.4 | Craniometric measures (external measurements of linear dimensions of the skull)

On the basis of the method of Martin (1928), we measured dimensions of the cranial vault on MRI images, determining the maximum cranial length (from Glabella to Opisthocranion), maximum cranial height (from

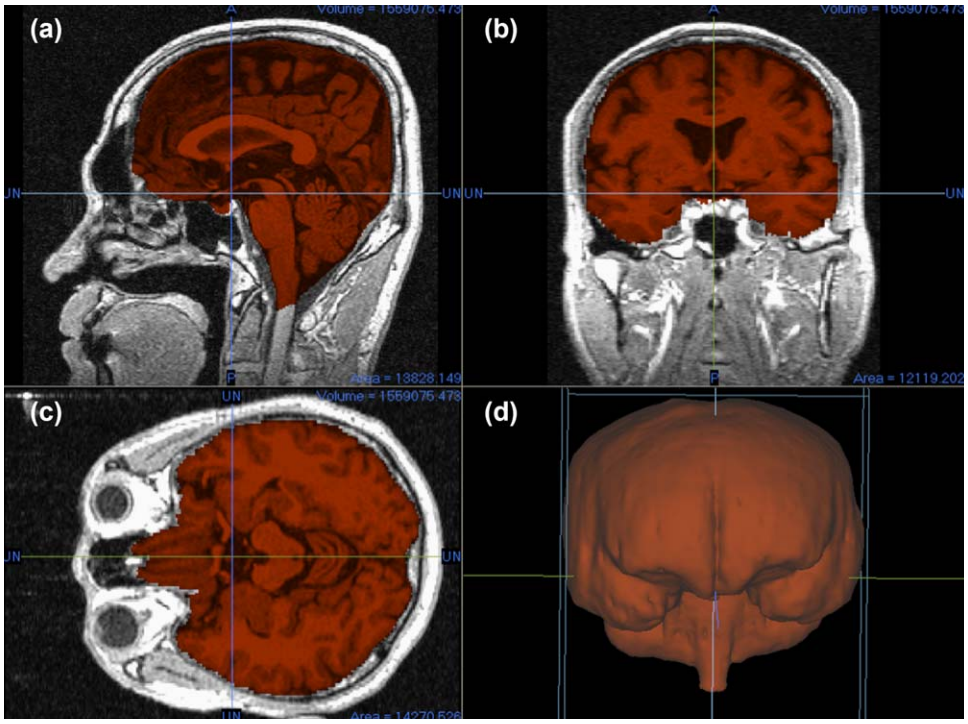

FIGURE 1 Demonstration of volumetry processes on 2D planes and 3D reconstruction of intracranial volume (ICV). The volumetry processes of gaining the ICV shown in (a) sagittal, (b) coronal, and (c) horizontal planes by manual detection method. (d) The 3D reconstruction of ICV is achieved by V-work 3.5 software

Basion to Bregma), and maximum cranial width (from left Eurion to right Eurion). We took the measurements three times and used the average of the three values for further analysis. The cephalic index was calculated by dividing the Eurion-Eurion breadth by the Glabella-Opisthocranion length.

2.5 | Statistical analysis

To assess the effects of birthyear and sex on the ICV and craniometric measurements, we analyzed the data using two-way analysis of variance (ANOVA) with birthyear (1930s, 1970s) and sex (male, female) as factors. The Pearson correlation coefficients were calculated in order to assess whether there was a relationship between intracranial volume and body parameters. All analyses were two-tailed, and a p value $<.05$ was considered as statistically significant (SPSS version 22.0; IBM, Armonk, NY). All data are represented as mean ± SD.

3 | RESULTS

3.1 | Intracranial volume

We compared the effect of birthyear and sex on the values of ICV and external measurements of cranial dimensions and BMI (Table 2). The average ICV of the 1930s group was 1502.27 ± 110.32 cm^3 for males and 1335.99 ± 53.00 cm^3 for females. The average ICV of the 1970s group was 1594.08 ± 99.46 cm^3 for males and 1425.94 ± 79.63 cm^3 for females (Figure 2). The ICV was normally distributed ($p > .05$) for each side and each sex in two birth cohorts. ANOVA revealed statistically significant difference in ICV between the old and young groups [F (1, 111) = 29.37, $p < 0.001$] and between males and females [F (1, 111) = 99.44, $p < 0.001$]. There was no significant interaction between birthyear and sex [F (1, 111) = 0.003, $p = 0.95$].

Pearson correlation coefficients for the relationship between the ICV and body parameters are presented in Table 3. The ICV was significantly correlated with body height in male ($r = 0.53$, $p < 0.001$) and female ($r = 0.26$, $p < 0.05$) subjects. A significant correlation was found between ICV and body weight in male ($r = 0.32$, $p < 0.05$) but not in female subjects. When data from both male and female subjects were pooled, height ($r = 0.68$, $p < 0.001$) and weight ($r = 0.48$, $p < 0.001$) effect on ICV were increased considerably.

3.2 | Craniometric measurement

Two-way ANOVA was carried out for each cranial measure. Each cranial measure was significantly larger in the 1970s groups than in the 1930s groups (Figure 2): height [F (1, 111) = 25.774, $p < 0.001$], length [F (1, 111) = 6.172, $p = 0.014$], and breadth [F (1, 111) = 9.266, $p = 0.003$]. Moreover, each cranial measure was significantly larger in men than in women: height [F (1, 111) = 44.501, $p < 0.001$], length [F (1, 111) = 29.443, $p < 0.001$], and breadth [F (1, 111) = 42.477, $p < 0.001$]. For cranial length, there was significant association interactions between birthyear and sex [F (1, 111) = 7.780, $p = 0.006$]; as it increased in men but remained steady in women.

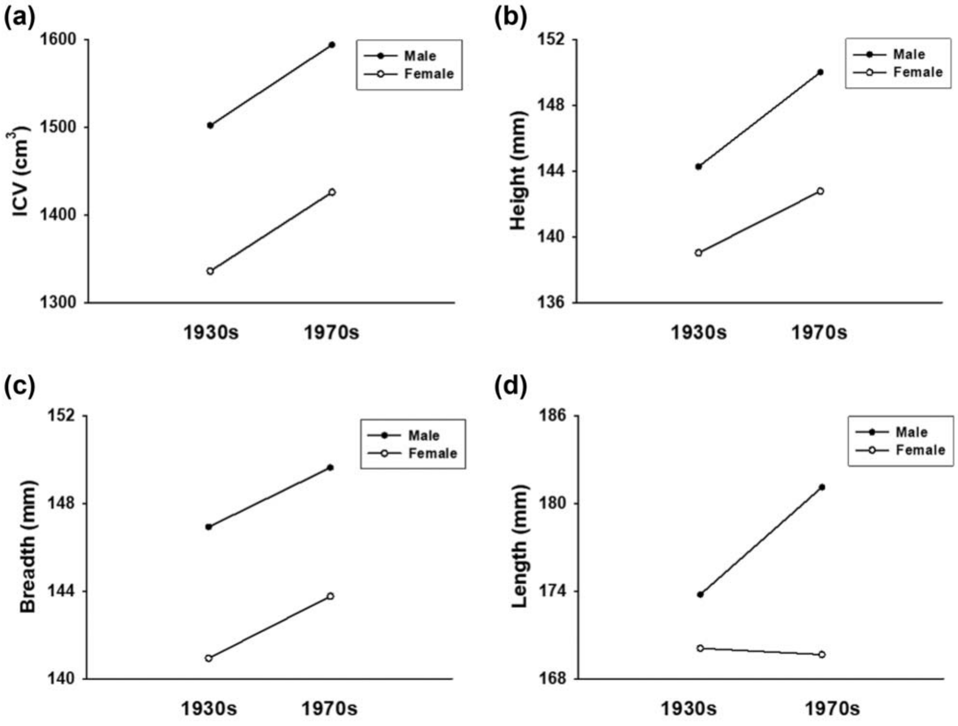

FIGURE 2 Intracranial volume and cranial measurements divided by birth cohorts and sex. (a–c) The ICV, cranial height, and breadth were increased in both sexes of two birth cohorts. (d) The cranial length was increased in males, whereas no difference was observed in female

3.3 | Cephalic index

From the 1930s to 1970s, the cephalic indices decreased for men, from 0.846 to 0.828 but increased for women, from 0.831 to 0.850. Two-way ANOVA showed that the observed change in the cephalic index between the 1930s group and the 1970s group was insignificant [F (1, 111) = 0.000, $p = 0.985$], but there was a marginal interaction between birthyear and sex, as depicted in Figure 3 [F (1, 111) = 3.740, $p < 0.056$].

3.4 | Body mass index

Two-way ANOVA revealed significant differences in BMI between the two birth cohorts [F (1, 111) = 13.48, $p < 0.001$] and between males and females [F (1, 111) = 13.72, $p < 0.001$]. There was significant interaction between birthyear and sex [F (1, 111) = 16.22, $p < 0.001$]; as it decreased in women but remained stable in men.

4 | DISCUSSION

In last century, few researchers have reported that cranial breadth and length have continuously increased in Korean population, with significant increases observed between 1950 and 1960 (Koh et al., 2001; Min, 2012). Our 1930s subjects suffered devastating historical events in their early childhood, whereas 1970s subjects were born after rapid industrialization (1960–1970). Therefore, these two generations are excellent samples to demonstrate environmental factor occurring any phenotypic change during socioeconomical transition.

TABLE 2 Effects of birthyear and sex on the intracranial volume (ICV), cranial measurements, and BMI

	1930s		1970s		p value		
Measurement	Men ($n = 32$)	Women ($n = 26$)	Men ($n = 28$)	Women ($n = 29$)	Birthyear	Sex	Birthyear × sex
ICV (cm^3)	1502.3 ± 110.3	1336.0 ± 53.0	1594.1 ± 99.5	1425.9 ± 79.6	<.001	<.001	.956
Height (mm)	144.3 ± 5.3	139.0 ± 5.6	150.0 ± 4.0	142.8 ± 5.0	<.001	<.001	.287
Length (mm)	173.8 ± 5.9	170.1 ± 7.5	181.1 ± 7.5	169.7 ± 8.9	.014	<.001	.006
Breadth (mm)	146.9 ± 4.7	140.9 ± 4.7	149.6 ± 5.5	143.8 ± 4.6	.003	<.001	.949
Cranial index	0.85 ± 0.04	0.83 ±0.06	0.83 ± 0.05	0.85 ± 0.06	0.985	0.730	0.056
BMI (kg m^{-2})	23.1 ± 1.9	23.2 ± 2.8	23.2 ± 3.0	19.9 ± 1.4	<.001	<.001	<.001

mean ± SD.

TABLE 3 Correlation of ICV and body parameters

	Male subjects ($n = 60$)			Female subjects ($n = 55$)			Total subjects ($n = 115$)		
	Height	Weight	BMI	Height	Weight	BMI	Height	Weight	BMI
ICV	0.53** ($p < .001$)	0.32* ($p = .012$)	0.03 ($p = 0.81$)	0.26* ($p = .048$)	−0.21 ($p = .11$)	−0.32* ($p = 0.017$)	0.68** ($p < .001$)	0.48** ($p < .001$)	0.11 ($p = 0.22$)

*$p < 0.05$, **$p < 0.001$.

4.1 | Secular changes in ICV

We compared the intracranial volume of two different generations of the Koreans, with birth year from 1926–1936 (1930s) and 1972–1979 (1970s), and found that cranial vaults of both male and female have increased by more than 90 cm^3. Comparing cranial volumes from previous studies with subjects born before or around the 1930s, we noted that cranial capacity remained relatively stable in these earlier generations from the late 19th and early 20th centuries. On the other hand, ICV increased significantly afterward, as shown in our subjects born in the 1970s.

In the last two centuries, a secular increase in cranial volume has been observed in other parts of the world. From mid-19th to 20th centuries, ICV had increased by at least 150 cm^3 in Americans, as well as in many European population (Jantz and Meadows Jantz, 2000, 2016; von Bonin, 1934). Although some researchers argue that intelligence is related to cranial volume (Lynn, 1990; Mingroni, 2004), we found no evidence correlating the secular changes in the ICV with intelligence in Korean population as previously reported (Henneberg, Budnik, Pezacka, & Puch, 1985).

4.2 | Secular changes in cranial shape

The increase in ICV was accompanied by changes in dimensional measures of skull. Although Western studies showed that the decrease in cranial breadth best explains the increase in ICV (Wescott & Jantz, 2005), increases in breadth and length have also contributed to the larger vaults for Koreans. In our study, the lateral and vertical expansion was evident in all subjects regardless of their sexuality, whereas increase in cranial length was only observed in males.

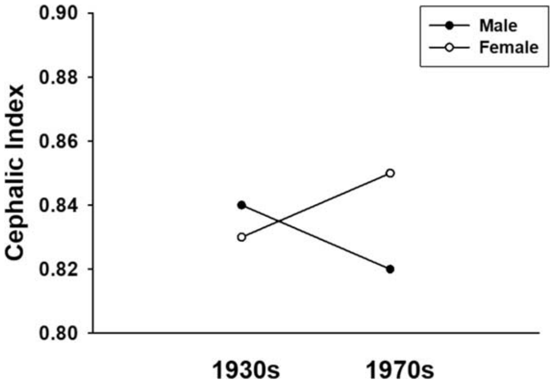

FIGURE 3 Cephalic indices of two birth cohorts. The cephalic index was decreased in males between two birth cohorts, whereas it increased in females

Previously, the secular changes in cranial breadth and length showed no significant difference between sexes before 1990s in Asian populations (Koh et al., 2001; Kouchi, 2000). In addition, the morphological classification of neurocrania showed no difference between sexes from 1950s to 1970s in Koreans (Hur, Kim, & Kang, 2008). However, we found different patterns of cranial shape change between male and female subjects, separated by four decades in birth. The men's cranial length increased more than cranial breadth, and as a result the cephalic indices decreased—that is, the cranium became narrower relative to cranial length. This is inconsistent with previous studies demonstrating that brachycephalization ceased and debrachycephalization began in Asian males (Hossain, Lestrel, & Ohtsuki, 2005; Koh et al., 2001; Kouchi, 2000). On the other hand, cranial breadth increased but the length remained stable among the women, and thus the cephalic index increased, indicating the cranium became relatively broader. Thus, these secular changes in opposite patterns reflect the sexual dimorphism within Korean population.

4.3 | ICV, skull morphology, and physical allometry

The rapid growth of head dimensions happens in the first year of life; hence, changes in skull have likely occurred in early childhood (Boas, 1912; Jantz and Meadows Jantz, 2000; Rushton and Osborne, 1995). In the last 100 years, improved nutritional status in early life has accelerated brain growth greatly, and humans now attain adult brain size at a younger age (Kretschmann, Schleicher, Wingert, Zilles, & Loblich, 1979). Earlier attainment of adult size suggests reduced time used for later posterior growth of the brain, which leads to shorter cranial length. This can direct a greater amount of cranial growth toward other vectors that are determined by genetics and thus population-specific. For example, secular changes of body height were accompanied by an increase of head length and a decrease of breadth in Europeans (Buretic-Tomljanovic et al., 2004; Weisensee and Jantz, 2011). In contrast, changes in body height were accompanied by a preferential lateral increase of the skull growth among Northern Mongolians, Japanese, and Mexicans (Kondo, Wakatsuki, & Shibagaki,, 1999; Kouchi, 2000; Little, Buschang, Reyes, Tan, & Malina, 2006).

Similarly, the positive correlation between the ICV and body size is well known (Dekaban and Sadowsky, 1978; Koh et al., 2001; Suh et al., 2015). The body stature of Koreans continued to increase during 20th century (Shin, Oh, Kim, & Hwang, 2012); likewise, the ICV showed a secular increase between two birth cohorts. Among other body parameters, height was significantly correlated with ICV in both subjects, suggesting that accelerated growth and higher stature influences the brain and thereby cranial development. BMI has unexpectedly a negative correlation with the ICV of females. Although BMI is a relative variable compared to height, we assume that females in their twenties (born 1970s) are the main contributor to this correlation because young females are affected by idealized body image and related weight management (Lee and Cho, 2013).

4.4 | Driving force of skull remodeling

General improvement in living environments across the world through industrialization has removed limitations on physical growth, including body size and skull volume. The rate and timing of growth and development was no longer hampered by disease and malnutrition (Weisensee and Jantz, 2011). In both Americans and Europeans, poor living standards at the beginning of the industrial revolution suppressed the growth of cranial vault, but with urbanization and socioeconomic advancement, cranial capacity started increasing at the end of late 19th and early 20th century (Mays, 2010). The environment of well-supplied nutrition, lower infant mortality, and better health care are all known to contribute to the growth of skull vault.

We speculated that delayed cessation of brachycephalization shown in our subjects is probably due to historical events that delayed economic progress. In early 20th century, Japanese colonization and the devastating Korean War halted the country's economic growth. Koreans experienced severe malnutrition by lack of food supply due to colonial exploitation particularly in 1930s. Despite the food aid from the US, the food supply was insufficient during the Korean War, which resulted in deficiency of proteins, vitamins, and calcium (Lee, Joo, Ahn, & Ryu 1988). In addition, Koreans could not receive any medical care in the absence of national health care system. Since the mid-1960s, South Korea experienced industrialization and rapid socioeconomic transition in the second half of the 20th century, as observed in a dramatic increase in GDP after 1970 (Heo, 2012).

Changes in socioeconomic status influenced every aspect of living: the nutritional level, dietary changes, and improved overall health care including infant and post-neonatal care, which are known to influence cranial size and shape (Ivanovsky, 1923; Lieberman, Krovitz, Yates, Devlin, & Claire, 2004; Miller and Corsellis, 1977). Taken together, the changes observed in this study is most likely the result of cranial plasticity resulting from the rapid social changes in Korea during the 20th century.

4.5 | Further research

Our research included two birth cohorts for the sampling and statistical analysis. Although many researchers agree that the cranium is mainly resistant to evolutionary change in the structure (Jenkins et al., 2000; LeMay, 1984; Liu et al., 2003), additional longitudinal studies would be helpful to determine the effect of aging or pathological conditions that might affect the cranial vaults. Follow-up studies with subjects of continuous age would clearly demonstrate the intersexual difference in the inflection points of secular changes in skull morphology. In addition, studies with large population would reinforce our findings on the cranial remodeling of Korean population. Despite these limitations, our findings are sufficient to observe the secular changes of ICV and skull shape since Koreans share the same ethnic background with less heterogeneity.

5 | CONCLUSION

We observed a significant increase in cranial volume in the Korean population in the last century over four decades accompanied by a change in cranial shape, which occurred differently between male and female. In both sexes, the cranium became taller, which is closely related to the cranial volume, although the cranium became relatively narrower for males and broader for females. The change observed in this study is most likely the result of cranial plasticity resulting from the rapid socioeconomic changes in Korea during the 20th century. However, the pattern of secular changes differs from Western populations and even between male and female, which imply the multifactorial nature of cranial morphology and development.

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