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# Age-Related Changes in the Cranial Thickness of Japanese Macaques (*Macaca fuscata*)

## Cambios Relacionados con la Edad en el Grosor Craneal de los Macacos Japoneses (*Macaca fuscata*)

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**SUMMARY:** Craniometry has revealed that continuous skull expansion occurs after dental maturity in macaques and other nonhuman primates. Endocranial volume has been shown to increase with age from mid-adulthood to older age in macaques. Thus, neurocranial thickness may decrease with age, especially from mid-adulthood to older age. Here, we investigated age-related changes in the cranial thickness of Japanese macaques (*Macaca fuscata*). Ten cranial thickness measurements (ten neurocranial landmarks) were made using computed tomographic scans of 140 crania from adult macaques (67 males and 73 females). The cranial thickness at many sites was shown to increase in the neurocranium from young adulthood (7–9 years) to early-mid adulthood (14–19 years) in males and late-mid adulthood (19–24 years) in females, while it was decreased in the oldest age group (>24 years). The cranial thickness at various sites showed a significant decrease from mid-adulthood to very old age in both sexes, although females had more sites with decreasing thickness than did males. The difference between sexes in terms of age-related changes in cranial thickness at sites on the mid-sagittal plane may be associated with the differences in the size of the projecting face and canines between males and females. The greater number of sites with decreasing thickness in females than in males may be associated with postmenopausal estrogen depletion in female macaques.

**KEY WORDS: Age-related changes; Cranial Thickness; Neurocranium; Macaques.**

## INTRODUCTION

Bone is an organ that shows deterioration with age in both humans and nonhuman primates (Mazess, 1982; Black *et al*., 2001), and changes in bones are therefore considered to be representative of physical aging (Pomchote, 2015). Age-related changes in human cranial thickness have been previously studied and are receiving an increasing amount of attention. For example, forensic research has focused on the relationship between cranial thickness and sex, age, and general body build (Lynnerup, 2001), as well as the correlation between age and risk of skull fracture (Torimitsu *et al*., 2014). Postcranial skeletal changes with age are evident in both humans and nonhuman primates. Continuous expansion of the medullary cavity in postcranial skeletons and age-related thinning of the cortex of long bones have been documented in various bones in both humans and nonhuman primates (Smith & Walker, 1964; Garn *et al*., 1967; Bowden *et al*., 1979; Kimura, 1994; Morbeck *et al*., 2002). However, there is still controversy with respect to age-related changes in cranial thickness in adult humans. A small increase in the thickness of the skull during adulthood has been suggested in some studies (Israel, 1973; Adeloye *et al*., 1975), but others have reported no correlation between age and cranial thickness (Tallgren, 1974; Lynnerup). Potential reasons for these contradictory conclusions include sampling bias, small sample size, confounding effects of pathology, and methodologies in data collection (Ross *et al*., 1998; Lynnerup).

Studies to delineate definite age-related changes in cranial thickness in humans have to be performed within the bounds of legal, ethical, and practical restrictions imposed in human experiments (Colman & Binkley, 2002). Studies involving other mammals are therefore a more appropriate approach to model human skeletal changes with advancing age, and nonhuman primates have been commonly used as substitute models (Walker, 1995; Colman & Binkley). Macaques are

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considered as a good model used to study the postcranial skeleton in aging humans because they age at a rate of approximately 2.5–3.5 times that of humans (Tigges *et al*., 1988; Duncan *et al*., 2011). In addition, macaques have shown an age-related decrease in cortical thickness and bone loss in the postcranial skeleton similar to those of humans (Bowden *et al*.; Colman & Binkley). However, no studies have been carried out on age-related changes in the cranial thickness of macaques.

The cranial dimension has been demonstrated to increase after dental maturity in macaques and other nonhuman primates (Jones *et al*., 2000; Wang *et al*., 2007; Balolia *et al*., 2013; Van Minh *et al*., 2015), as manifested by a slight expansion of the cranial vault. Endocranial volume has also been shown to increase from mid-adulthood to older age in macaques (Van Minh & Hamada, 2017). Thus, neurocranial thickness may decrease with age, especially from mid-adulthood onward.

The aim of the present study was to investigate age-related changes in the craniofacial thickness of Japanese macaques (*Macaca fuscata*) of known age and origin, reared in the same condition. Craniometric measurement of age-related changes have shown that several sizes of the cranium developed in response to muscular force, reproductive cessation, and whole-body aging in macaques (Van Minh *et al*., 2015). We therefore examined whether age-related changes in cranial thickness are associated with these factors. Because changes in cranial size after dental maturity differ between sexes (Wang *et al*.; Van Minh *et al*., 2015), we expected to find similar patterns in age-related changes in the cranial thickness of Japanese macaques. Based on the results of the present study, we discussed the implications of age-related changes in human cranial thickness.

## MATERIAL AND METHOD

We examined the thickness of 140 crania from adult Japanese macaques of known age (67 males and 73 females) at the Primate Research Institute (PRI) at Kyoto University, Japan. All macaque subjects originated from the Arashiyama, Takahama, and Wakasa areas. The subjects were reared in corral cages and fed monkey chow and sweet potatoes. Subjects died a natural death and no effect of disorders was detected on their cranial bones. The macaques did not suffer from any serious disease nor were subjected to serious experimental treatments. Healthy younger subjects were sacrificed for other experiments. The ages of the macaques were expressed as a decimal fraction of years in age. The ages of male and female subjects ranged from 7.0 to 26.9 years and from 7.0 to 30.7 years, respectively. The subjects were divided into five age groups: 7.0–8.9 years (10 males and 10 females), 9.0–13.9 years (25 males and 25 females), 14.0–18.9 years (17 males and 23 females), 19.0–23.9 years (9 males and 7 females), and 24.0 years or more (6 males and 8 females).

**Data collection.** Computed tomographic scans of the cranium were performed using a helical scanner (Asteion Premium 4 Editions; Toshiba Medical Systems, Japan) at the PRI, with a pixel size of 0.25 mm × 0.25 mm and a 0.5-mm interval between slices. The orientation of the slices was parallel to the axial or coronal plane.

Cranial thickness measurements were taken from ten sites on the neurocranium of each individual (Fig. 1): MBN, midpoint between the bregma and nasion; AB, 1 cm anterior to the bregma; B, bregma; LB, 1 cm to the left of the

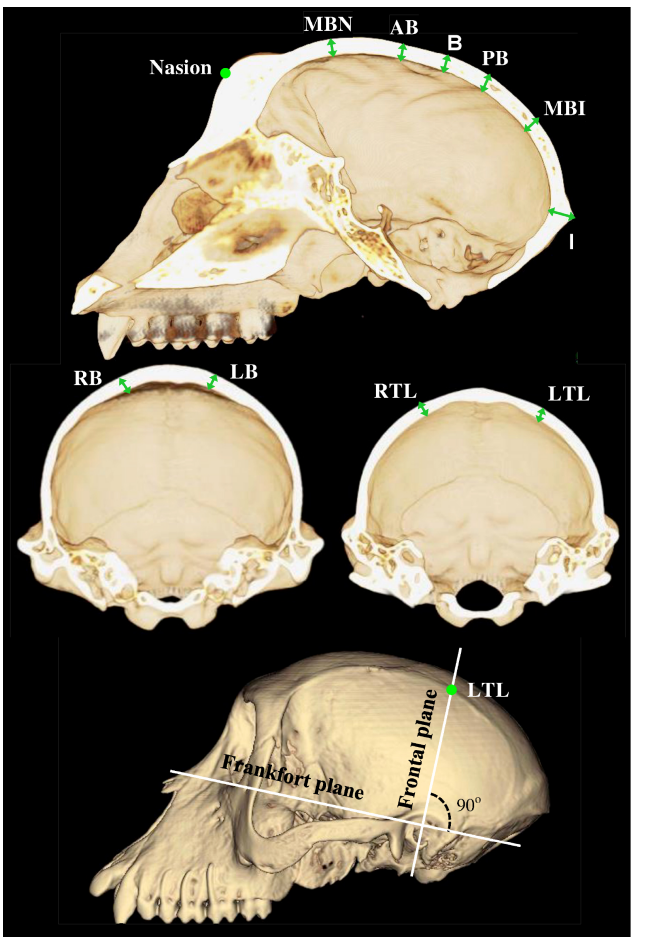


Fig. 1 Sites on the neurocranium for measurements of thickness. MBN: midpoint between the bregma and nasion; B: bregma; AB: 1 cm anterior to the bregma; PB: 1 cm posterior to the bregma; LB: 1 cm to the left of the bregma; RB: 1 cm to the right of the bregma; MBI: midpoint between the bregma and inion; I: inion; LTL: left temporal line; and RTL: right temporal line.

bregma; RB, 1 cm to the right of the bregma; PB, 1 cm posterior to the bregma; MBI, midpoint between the bregma and inion; I, inion; LTL, left temporal line; and RTL, right temporal line (the cranial thickness at the temporal line was measured at the site of intersection between the frontal plane and temporal line). All thickness measurements at the neurocranium were taken perpendicular to the external cranial surface, except for the thickness at the inion, which was taken perpendicular to the internal cranial surface. All measurements were acquired using three-dimensional reconstructed images on a computer screen using the AZE Virtual Place software (AZE Co., Ltd., Tokyo, Japan). The thickness of each specimen was measured without knowledge of sex or age (Lynnerup). Measurements were made three times by the same observer and the average value was obtained for analysis.

**Statistical analysis.** All statistical analyses were performed using functions of Excel (Microsoft Co. Ltd.) or Past (version 2.17 software; Hammer *et al*., 2001) with significance determined at $p < 0.05$. The t-test was used to assess whether there were sex-related differences in cranial thickness. The cranial thickness measurements between age groups were analyzed by Kruskal-Wallis tests with post-hoc testing performed separately for males and females.

## RESULTS

The mean and standard deviation of cranial thickness measurements at the ten sites of the neurocranium are presented in Table I. To analyze the difference between sexes, we pooled age groups in each sex (Table I). Cranial thickness was significantly greater in males than in females ($p < 0.05$; at MBN, AB, B,, PB, MBI, LTL, RTL, and I). There were no significant lateral differences in the cranial thickness between LB and RB and between LTL and RTL in each sex.

Table I. Mean, standard deviation, and difference in cranial thickness of each sample point between male and female.

| Variable | Males (n = 67) | Females (n = 73) | Difference between males and females (%) | *P* value |
|---|---|---|---|---|
| MBN | $3.34 \pm 0.58^{+}$ | $3.07 \pm 0.50^{+}$ | 8.8 | < 0.01** |
| AB | $3.65 \pm 0.69^{+}$ | $3.22 \pm 0.56^{+}$ | 13.5 | < 0.001*** |
| B | $4.11 \pm 0.62^{+}$ | $3.53 \pm 0.65^{+}$ | 16.3 | < 0.001*** |
| LB | $3.19 \pm 0.57^{+}$ | $3.21 \pm 0.47^{+}$ | –0.6 | 0.824 |
| RB | $3.19 \pm 0.55^{+}$ | $3.22 \pm 0.52^{+}$ | –0.9 | 0.675 |
| PB | $3.90 \pm 0.69^{+}$ | $3.32 \pm 0.49^{+}$ | 17.5 | < 0.001*** |
| MBI | $3.94 \pm 0.65^{+}$ | $3.65 \pm 0.51^{+}$ | 7.9 | < 0.01** |
| LTL | $3.65 \pm 0.76^{+}$ | $3.09 \pm 0.44^{+}$ | 18.4 | < 0.001*** |
| RTL | $3.63 \pm 0.77^{+}$ | $3.05 \pm 0.46^{+}$ | 19.0 | < 0.001*** |
| I | $6.19 \pm 1.24^{+}$ | $5.46 \pm 1.10^{+}$ | 13.4 | < 0.001*** |

+ Mean ± standard deviation (SD) mm. **–*** Statistically significant differences between males and females (t-test) at ** $p < 0.01$ and *** $p < 0.001$.

The cranial thickness of the various age groups is presented in Tables II and III. The cranial thickness at many sites showed an age-dependent change pattern of increase-peak-decrease (Table II). Changes in cranial thickness with age were significant ($p < 0.05$) at nine sites in both males and females (Table II).

The common pattern of age-related changes in cranial thickness at the sites of the neurocranium was an increase from young adulthood (7–9 years) to early-mid adulthood (14–19 years) in males and late-mid adulthood (19–24 years) in females, followed by a decrease with age (Tables II and III). However, the pattern of age-related change was somewhat different between males and females. The thickness at the MBN, PB, and MBI increased significantly in males, peaking at 14–19 years with an increase of 23.23% ($p < 0.01$), 20.86% ($p < 0.01$), and 23.14% ($p < 0.01$), respectively. We observed a decrease in thickness at these sites following each peak, but it was not statistically significant. On the other hand, the cranial thickness in females at these sites only increased slightly, peaking at 19–24 years, followed by a significant decrease in thickness of 23.78% ($p < 0.01$), 24.67% ($p < 0.01$), and 19.51% ($p < 0.01$), respectively.

The thickness at B and AB showed a significant decrease of 30.32% and 28.42%, respectively, from late-mid adulthood (19-24 years) to the oldest age (>24 years) ($p < 0.01$) in females, whereas these thicknesses only changed slightly in males. At LB and RB, the thickness increased slightly with age from young adulthood (7–9 years) to early-mid adulthood (14–19 years) in males and late-mid adulthood (19–24 years) in females and subsequently decreased significantly in both sexes.

The thickness at LTL and RTL also showed the same trend in both sexes, with a significant increase from young adulthood (7–9 years) to late-mid adulthood (19–24 years) followed by a stable period from late-mid adulthood to the oldest age (>24 years). The thickness at the temporal line (LTL and RLT) increased with age, whereas the thickness near the bregma (RB and LB) decreased. The location of the temporal line also ascended along the lateral wall of the cranial vault with age in males, but not in females. Thickening was also highlighted by the thinning of plain neurocranium (RB and LB).

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Table II. Age-related changes in cranial thickness in males and females.

| Variable | Age group (years) | Male | | | Female | | |
|---|---|---|---|---|---|---|---|
| | | Mean (mm) | SD | Age difference | Mean (mm) | SD | Age difference |
| MBN | 7–9 | 2.97 (n = 10) | 0.39 | b**, c* | 3.01 (n = 10) | 0.30 | |
| | 9–14 | 3.22 (n = 25) | 0.57 | e*, f* | 3.08 (n = 25) | 0.47 | g* |
| | 14–19 | 3.66 (n = 17) | 0.63 | b**, e* | 3.09 (n = 23) | 0.54 | k* |
| | 19–24 | 3.62 (n = 9) | 0.48 | c*, f* | 3.49 (n = 7) | 0.44 | l** |
| | >24 | 3.17 (n = 6) | 0.40 | | 2.66 (n = 8) | 0.35 | g*, k*, l** |
| AB | 7-9 | 3.15 (n = 10) | 0.60 | b**, c* | 3.10 (n = 10) | 0.35 | d* |
| | 9-–14 | 3.53 (n = 25) | 0.58 | e* | 3.20 (n = 25) | 0.46 | g* |
| | 14–19 | 4.03 (n = 17) | 0.82 | b**, e* | 3.23 (n = 23) | 0.52 | k* |
| | 19–24 | 3.84 (n = 9) | 0.48 | c* | 3.80 (n = 7) | 0.76 | l** |
| | >24 | 3.57 (n = 6) | 0.63 | | 2.72 (n = 8) | 0.58 | d*, g*, k*, l** |
| B | 7–9 | 3.98 (n = 10) | 0.76 | | 3.70 (n = 10) | 0.49 | d** |
| | 9–14 | 3.98 (n = 25) | 0.63 | | 3.54 (n = 25) | 0.63 | g** |
| | 14–19 | 4.38 (n = 17) | 0.51 | | 3.51 (n = 23) | 0.56 | k** |
| | 19–24 | 4.31 (n = 9) | 0.48 | | 4.09 (n = 7) | 0.79 | l** |
| | >24 | 3.78 (n = 6) | 0.56 | | 2.85 (n = 8) | 0.46 | d**, g**, k**, l** |
| LB | 7–9 | 3.24 (n = 10) | 0.59 | d* | 3.17 (n = 10) | 0.28 | d** |
| | 9–14 | 3.27 (n = 25) | 0.52 | g** | 3.18 (n = 25) | 0.41 | g** |
| | 14–19 | 3.38 (n = 17) | 0.54 | k** | 3.33 (n = 23) | 0.51 | k** |
| | 19–24 | 2.95 (n = 9) | 0.62 | | 3.57 (n = 7) | 0.54 | l** |
| | >24 | 2.61 ( n = 6) | 0.33 | d*, g**, k** | 2.70 (n = 8) | 0.27 | d**, g**, k**, l** |
| RB | 7–9 | 3.27 (n = 10) | 0.58 | d* | 3.17 (n = 10) | 0.45 | d** |
| | 9–14 | 3.19 (n = 25) | 0.51 | g** | 3.19 (n = 25) | 0.43 | g** |
| | 14–19 | 3.40 (n = 17) | 0.39 | k** | 3.34 (n = 23) | 0.59 | k** |
| | 19–24 | 3.04 (n = 9) | 0.79 | | 3.63 (n = 7) | 0.57 | l** |
| | >24 | 2.63 (n = 6) | 0.25 | d*, g**, k** | 2.71 (n = 8) | 0.33 | d**, g**, k**, l** |
| PB | 7–9 | 3.50 (n = 10) | 0.77 | b**, c* | 3.48 (n = 10) | 0.25 | d* |
| | 9–14 | 3.76 (n = 25) | 0.65 | e* | 3.27 (n = 25) | 0.44 | g* |
| | 14–19 | 4.23 (n = 17) | 0.54 | b**, e* | 3.32 (n = 23) | 0.49 | k* |
| | 19–24 | 4.18 (n = 9) | 0.70 | c* | 3.77 (n = 7) | 0.61 | l** |
| | >24 | 3.82 (n = 6) | 0.71 | | 2.84 (n = 8) | 0.30 | d*, g*, k*, l** |
| MBI | 7–9 | 3.50 (n = 10) | 0.58 | b** | 3.72 (n = 10) | 0.52 | |
| | 9–14 | 3.78 (n = 25) | 0.49 | e** | 3.64 (n = 25) | 0.49 | |
| | 14–19 | 4.31 (n = 17) | 0.60 | b**, e** | 3.65 (n = 23) | 0.55 | |
| | 19–24 | 4.20 (n = 9) | 0.68 | | 4.05 (n = 7) | 0.40 | l** |
| | >24 | 3.87 (n = 6) | 0.92 | | 3.26 (n = 8) | 0.38 | l** |
| LTL | 7–9 | 2.93 (n = 10) | 0.47 | a*, b*, c**, d* | 2.90 (n = 10) | 0.23 | c** |
| | 9–14 | 3.55 (n = 25) | 0.68 | a*, f* | 2.98 (n = 25) | 0.31 | f** |
| | 14–19 | 3.87 (n = 17) | 0.72 | b** | 3.08 (n = 23) | 0.40 | |
| | 19–24 | 4.21 (n = 9) | 0.83 | c**, f* | 3.55 (n = 7) | 0.77 | c**, f** |
| | >24 | 3.85 (n = 6) | 0.59 | d* | 3.26 (n = 8) | 0.52 | |
| RTL | 7–9 | 2.99 (n = 10) | 0.59 | a*, b**, c** | 2.90 (n = 10) | 0.29 | c** |
| | 9–14 | 3.43 (n = 25) | 0.66 | a*, e*, f* | 2.89 (n = 25) | 0.32 | f* |
| | 14–19 | 3.93 (n = 17) | 0.68 | b**, e* | 3.06 (n = 23) | 0.42 | |
| | 19–24 | 4.19 (n = 9) | 0.86 | c**, f** | 3.52 (n = 7) | 0.78 | c**, f* |
| | >24 | 3.82 (n = 6) | 0.70 | | 3.27 (n = 8) | 0.53 | |
| I | 7–9 | 5.66 (n = 10) | 0.53 | c**, d** | 5.22 (n = 10) | 0.38 | |
| | 9–14 | 5.77 (n = 25) | 1.13 | f*, g** | 5.16 (n = 25) | 0.93 | |
| | 14–19 | 6.40 (n = 17) | 1.40 | | 5.75 (n = 23) | 1.43 | |
| | 19–24 | 6.71 (n = 9) | 1.35 | c**, f** | 5.67 (n = 7) | 0.83 | |
| | >24 | 7.49 (n = 6) | 0.59 | d**, g** | 5.66 (n = 8) | 0.93 | |

a-l Statistically significant differences between age groups (Kruskal-Wallis) at * $p < 0.05$ and ** $p < 0.01$ for a 7–9 vs. 9–14 years, b 7–9 vs. 14–19 years, c 7–9 vs. 19–24 years, d 7–9 vs. >24 years, e 9–14 vs. 14–19 years, f 9–14 vs. 19–24 years, g 9–14 vs >24 years, h 14–19 vs. 19–24 years, k 14–19 vs. >24 years, l 19–24 vs. >24 years.

at other sites in the neurocranium in males, with a significant increase ($p < 0.01$) of 32.33% in the oldest age group (>24 years). By contrast, the thickness at this site changed only slightly in females.

Table III. Percentage change in cranial thickness between age groups in males and females.

| | 7–9 to 14–19 | 7–9 to 19–24 | 7–9 to >24 | 14–19 to >24 | 19–24 to >24 |
|---|---|---|---|---|---|
| Male | | | | | |
| MBN | 23.23** | 21.89* | 6.73 | –13.93 | –12.43 |
| AB | 27.94** | 21.90* | 13.33 | –11.41 | –7.03 |
| B | 10.05 | 8.29 | –5.03 | –13.70 | –12.30 |
| LB | 4.32 | –8.95 | –19.44* | –22.78** | –11.53 |
| RB | 3.98 | –7.03 | –19.57* | –22.65** | –13.49 |
| PB | 20.86** | 19.43* | 9.14 | –9.69 | –8.61 |
| MBI | 23.14** | 20.00 | 10.57 | –10.21 | –7.86 |
| LTL | 32.08** | 43.69** | 31.40* | –0.52 | –8.55 |
| RTL | 31.44** | 40.13** | 27.76 | –2.80 | –8.83 |
| I | 13.07 | 18.55* | 32.33** | 17.03 | 11.62 |
| Female | | | | | |
| MBN | 2.66 | 15.95 | –11.63 | –13.92* | –23.78** |
| AB | –0.68 | 16.85 | –16.36* | –15.79* | –28.42** |
| B | –5.14 | 10.54 | –22.97** | –18.80** | –30.32** |
| LB | 5.05 | 12.62 | –14.83** | –18.92** | –24.37** |
| RB | 5.36 | 14.51 | –14.51** | –18.86** | –25.34** |
| PB | –4.60 | 8.33 | –18.39* | –14.46* | –24.67** |
| MBI | –1.88 | 8.87 | –12.37 | –10.68 | –19.51** |
| LTL | 6.21 | 22.41** | 12.41 | 5.84 | –8.17 |
| RTL | 5.52 | 21.38** | 12.76 | 6.86 | –7.10 |
| I | 10.15 | 8.62 | 8.43 | –1.57 | –0.18 |

* $p < 0.05$ and ** $p < 0.01$ Comparison between age groups by Kruskal-Wallis test with post-hoc testing..

## DISCUSSION

Various factors including environment, genetics, and physiological conditions affect bone dimensions, making it difficult to define age-related changes in bone (Syed & Ng, 2010; Pomchote; Van Minh *et al*., 2015). In the present study, we controlled the origin of the subjects, rearing conditions (corral cages), and foods (monkey chow and potato supplements) throughout the lifetime of the experimental macaques.

Bone minerals in postcranial skeletons are generally absorbed more than deposited with advancing age (Chen *et al*., 2013). The thinning of the cortex of long bones with advancing age is thought to be the result of endosteal absorption in both humans and nonhuman primates (Smith & Walker; Garn *et al*.; Bowden *et al*.; Kimura; Morbeck *et al*.). Bone mineral loss starts in the middle age and is accelerated by estrogen deficiency (Colman & Binkley), and the expansion of long bone diameter is considered to be a mechanical compensation to thinning. Women display greater bone loss than men, especially at the postmenopausal stage (Riggs *et al*., 2008), and age-related changes in the craniofacial skeleton are also expected.

The main findings of the present study demonstrated significant age-related changes in the cranial thickness at many sites in the neurocranium, showing an increasing pattern from young adulthood (7–9 years) to early-mid adulthood (14–19 years) in males and late-mid adulthood (19–24 years) in females, followed by a decrease in the oldest age group (>24 years). Equivalent human ages are 21–27 years in both sexes, 42–57 years in males, 57–72 years in females, and >72 years in both sexes, respectively. The thickness at B, LTL, RTL, and AB in the neurocranium showed greater age-related changes than those at other sites in both males and females.

We also observed a difference between sexes in age-related changes in cranial thickness. The thickness at sites on the mid-sagittal plane significantly increased in males from young adulthood to mid-adulthood, though it did not show any significant change from mid-adulthood to very old age. This was especially evident in the thickness at the inion, which increased significantly with age in males. In contrast, the thickness at these sites in females did not increase significantly from young adulthood to mid-

adulthood but did show a significant decrease from mid-adulthood to the oldest age. This difference between the sexes may be associated with the differences in the sizes of the projecting face and canines between males and females (Mouri, 1994; Fukase, 2011), which leads to the development of masticatory and postural muscles and stimulates the increase in cranial thickness at these sites in males.

The thickness at the left and right of the bregma (away from the thickness of the plain cranial vault) showed the same age-related trend between the two sexes: a slight increase from young adulthood to mid-adulthood followed by a significant decrease from mid-adulthood to the oldest age. This may signify that the whole cranial vault may become thinner with age, especially from mid-adulthood onward. The thickening at the midsagittal plane sites (linear) may be a mechanical compensation as the buttress (crest) to support the neurocranium from the load to hold the head.

The results of studies on the human skull revealed age-related changes that are still controversy with respect to that in the cranial thickness of adult humans. Although a slight increase in the cranial thickness with age has been recorded (Israel; Adeloye *et al*.), Tallgren and Lynnerup reported that there was no correlation between age and cranial thickness during adult life in men and women. However, Torimitsu *et al*. recently reported that cranial thickness significantly decreased with age in Japanese women, but not in men. They suggested that cranial thickness may be greatly affected by absorption, which is essentially caused by postmenopausal bone loss in women (Torimitsu *et al*.). In the present study, the cranial thickness in macaques showed a significant decrease from mid-adulthood to the oldest age at many sites in both sexes, and females displayed thinning at a greater number of sites than males. We suggest that this may be associated with postmenopausal estrogen depletion in female macaques (Nozaki *et al*., 1995; Colman *et al*., 1999; Walker & Herndon, 2008; Hamada & Yamamoto, 2010), but further studies are required to evaluate the effect of subsequent menopause on the cranial thickness in female macaques.

The peak cranial thickness at many sites in the neurocranium occurred later in females than in males, corresponding to the finding that craniometric age changes were attained later in female than in male macaques (Wang *et al*.; Van Minh *et al*., 2015). Similarly, the maximal stages of trunk length and epiphyseal unions in the postcranial skeletons of Japanese macaques were reported to occur later in females than in males (Kimura; Hamada, 2008). Vertebral body dimensions in Japanese macaques have also been shown to peak later in females (15–20 years of age) than in males (10–15 years of age) (Pomchote). In the present study, the age at the peak cranial thickness was estimated to be 14–19 years and 19–24 years in males and females, respectively. The age at maximal skull size was estimated to be 16.0 ± 3.0 years and 20.2 ± 3.0 years in males and females, respectively (Van Minh *et al*., 2015). This difference between sexes might be related to reproductive activity in Japanese macaques, which differs between the two sexes. Females continue to reproduce until the cessation of reproduction in older age (around 18–25 years, with wide variation among individuals (Takahata *et al*., 1995). Therefore, adult females may exert more energy in the reproductive costs of pregnancy and the lactation period, which may lead to a slowing of cranial bone remodeling or growth. However, it is also possible for males to start aging earlier than females.

Age-related expansion of the cranium in Japanese macaques is thought to be associated with the development of bones in response to physical stress from the masticatory and/or postural muscles (Van Minh *et al*., 2015). Cranial and posterior basicranial lengths, which include the inion, increased significantly with age in male Japanese macaques (Van Minh *et al*., 2015). A significant relationship was found between age-related changes in the cranial thickness at the inion and cranial and posterior basicranial lengths in male macaques (Fig. 2). The results of the present study indicate that the thickness at the inion (development of tuberosity)

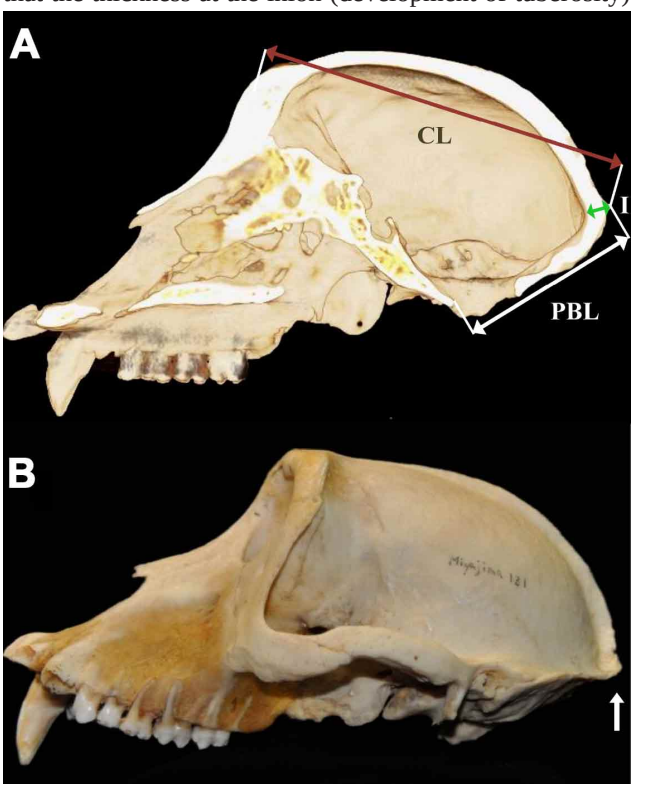


Fig. 2 (a) Relationship between measurements at the inion. Posterior basicranial length (PBL), cranial length (CL), and cranial thickness at the inion (I). (b) Bone development (tubercles, white arrow) around the inion in old male macaques.

increased significantly in males (1.83 mm on average) and showed a significant positive correlation with cranial length ($rp = 0.4859$, $p < 0.0001$) and posterior basicranial length ($rp = 0.4985$, $p < 0.0001$) with increments of 3.47 mm and 2.03 mm, respectively. The increases in cranial/posterior basicranial lengths are attributed to the development of the nuchal crest or tubercles, where the nuchal muscles are inserted. Owing to the same mechanical stress to retain the head posture, especially in males that have a longer projecting face and developed canines, the sites on the mid-sagittal plane, AB, and PB become thicker in males.

Cranial dimensions generally increased with age in Japanese macaques (Van Minh *et al*., 2015) from mid-adulthood to the oldest age, and this phenomenon has also been documented in humans (Garn *et al*.; Israel; Ruff, 1980). Cortical thickness decreases in the same age period. Therefore, the cranial cavity (endocranial volume) has been shown to be enlarged in older macaques (Van Minh *et al*., 2017), and this has been previously investigated in humans (Israel; Lazenby, 1990).

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**MINH, N. V.; DUONG, D. T.; LE, T. T. T.; HIRASAKI, E. & HAMADA, Y.** Cambios relacionados con la edad en el grosor craneal de los macacos Japoneses (*Macaca fuscata*). *Int. J. Morphol., 37(3)*:1142-1149, 2019.

**RESUMEN:** La craneometría ha revelado que la expansión continua del cráneo se produce después de la madurez dental en macacos y otros primates no humanos. Se ha demostrado que el volumen endocraneal aumenta con la edad desde mediados de la edad adulta hasta la edad más avanzada en macacos. Por lo tanto, el grosor neurocraneal puede disminuir con la edad, especialmente desde la edad adulta media hasta la edad avanzada. Aquí, investigamos los cambios relacionados con la edad en el grosor craneal de los macacos Japoneses (*Macaca fuscata*). Se realizaron diez mediciones del grosor craneal (considerando diez puntos de referencia neurocraneales) mediante tomografías computarizadas de 140 cráneos de macacos adultos (67 machos y 73 hembras). Se observó que el grosor craneal en muchos sitios aumentó en el neurocráneo desde la edad adulta joven (7–9 años) hasta la edad adulta media (14–19 años) en los hombres y en la edad adulta media tardía (19–24 años) en las mujeres, mientras que se redujo en el grupo de mayor edad (> 24 años). El grosor craneal en varios sitios mostró una disminución significativa desde la edad adulta media hasta la edad muy avanzada en ambos sexos, aunque las hembras tenían más sitios con grosor decreciente. La diferencia entre sexos, en términos de cambios relacionados con la edad, en el grosor craneal en los sitios en el plano mediano puede asociarse con las diferencias en el tamaño de la cara y en los caninos entre machos y hembras. El mayor número de sitios con grosor decreciente en las hembras respecto a los machos puede estar asociado con el agotamiento de los estrógenos posmenopáusicos en los macacos hembras.

**PALABRAS CLAVE: Cambios relacionados con la edad; Grosor craneal; Neurocráneo; Macacos.**

## REFERENCES

Adeloye, A.; Kattan, K. R. & Silverman, F. N. Thickness of the normal skull in the American Blacks and Whites. *Am. J. Phys. Anthropol., 43(1)*:23-30, 1975.

Balolia, K. L.; Soligo, C. & Lockwood, C. A. Sexual dimorphism and facial growth beyond dental maturity in great apes and gibbons. *Int. J. Primatol., 34(2)*:361-87, 2013.

Black, A.; Tilmont, E. M.; Handy, A. M.; Scott, W. W.; Shapses, S.A.; Ingram, D. K.; Roth, G. S. & Lane, M. A. A nonhuman primate model of age-related bone loss: a longitudinal study in male and premenopausal female rhesus monkeys. *Bone, 28(3)*:295-302, 2001.

Bowden, D. M.; Teets, C.; Witkin, J. & Young, D. M. Long Bone Calcification and Morphology. In: Bowden, D. M. (Ed.). *Aging in Nonhuman Primates*. New York, Van Vostrand Reinhold, 1979. Pp.335-47.

Chen, H.; Zhou, X.; Fujita, H.; Onozuka, M. & Kubo, K. Y. Age-related changes in trabecular and cortical bone microstructure. *Int. J. Endocrinol., 2013*:213234, 2013.

Colman, R. J. & Binkley, N. *Skeletal Aging in Macaque Monkeys.* In: Erwin, J. M. & Hof, P. R. (Eds.). Aging in Nonhuman Primates. Interdisciplinary Topics in Gerontology. Vol. 31. Basel, Karger, 2002. pp.32-47.

Colman, R. J.; Kemnitz, J. W.; Lane, M. A.; Abbott, D. H. & Binkley, N. Skeletal effects of aging and menopausal status in female rhesus macaques. *J. Clin. Endocrinol. Metab., 84(11)*:4144-8, 1999.

Duncan, A. E.; Colman, R. J. & Kramer, P. A. Longitudinal study of radiographic spinal osteoarthritis in a macaque model. *J. Orthop. Res., 29(8)*:1152-60, 2011.

Fukase, H. Relationship between canine dimorphism and mandibular morphology in the hamadryas baboon and the Japanese monkey. *Am. J. Phys. Anthropol., 144(4)*:607-16, 2011.

Garn, S. M.; Rohmann, C. G.; Wagner, B. & Ascoli, W. Continuing bone growth throughout life: a general phenomenon. *Am. J. Phys. Anthropol., 26(3)*:313-7, 1967.

Hamada, Y. & Yamamoto, A. *Morphological Characteristics, Growth and Aging in Japanese Macaques.* In: Nakagawa, N.; Nakamichi, M. & Sugiura, H. (Eds.). The Japanese Macaques. Springer, 2010. pp.27-52.

Hamada, Y. *Body Growth and Aging in Japanese Macaques*. In: Takatsuki, S. & Yamagiwa, J. (Eds.). Japanese Mammalogy 2: Medium and Large Mammals. Tokyo, University of Tokyo Press, 2008. pp.53-75.

Hammer, Ø.; Harper, D. A. T. & Ryan, P. D. PAST: *Paleontological statistics software package for education and data analysis.* Palaeontol. Electron., 4, 2001. Available from: https://palaeo-electronica.org/2001_1/past/issue1_01.htm

Israel, H. Age factor and the pattern of change in craniofacial structures.

*Am. J. Phys. Anthropol., 39(1)*:111-28, 1973.

Jones, A. L.; Degusta, D.; Turner, S. P.; Campbell, C. J. & Milton, K. Craniometric variation in a population of mantled howler monkeys (Alouatta palliata): evidence of size selection in females and growth in dentally mature males. *Am. J. Phys. Anthropol., 113(3)*:411-34, 2000.

Kimura, T. Age changes of postcranial skeletons in adult japanese macaques. *Anthropol. Sci., 102(Suppl.)*:27-41, 1994.

Lazenby, R. A. Continuing periosteal apposition. I: Documentation, hypotheses, and interpretation. *Am. J. Phys. Anthropol., 82(4)*:451-72, 1990.

Lynnerup, N. Cranial thickness in relation to age, sex and general body build in a Danish forensic sample. *Forensic Sci. Int., 117(1-2)*:45-51, 2001.

Mazess, R. B. On aging bone loss. *Clin. Orthop. Relat. Res., (165)*:239-52, 1982.

Morbeck, M. E.; Galloway, A. & Sumner, D. R. *Getting Old at Gombe: Skeletal Aging in Wild-Ranging Chimpanzees.* In: Erwin, J. M. & Hof, P. R. (Eds.). Aging in Nonhuman Primates. Interdisciplinary Topics in Gerontology. Vol 31. Basel, Karger, 2002. pp.48-62.

Mouri, T. Postnatal growth and sexual dimorphism in the skull of the Japanese macaque (*Macaca fuscata*). *Anthropol. Sci., 102(Supplement)*:43-56, 1994.

Nozaki, M.; Mitsunaga, F. & Shimizu, K. Reproductive senescence in female Japanese monkeys (*Macaca fuscata*): age- and season-related changes in hypothalamic-pituitary-ovarian functions and fecundity rates. *Biol. Reprod. 52(6)*:1250-7, 1995.

Pomchote, P. Age-related changes in osteometry, bone mineral density and osteophytosis of the lumbar vertebrae in Japanese macaques. *Primates, 56(1)*:55-70, 2015.

Riggs, B. L.; Melton, L. J.; Robb, R. A.; Camp, J. J.; Atkinson, E. J.; McDaniel, L.; Amin, S.; Rouleau, P. A. & Khosla, S. A population-based assessment of rates of bone loss at multiple skeletal sites: evidence for substantial trabecular bone loss in young adult women and men. *J. Bone Miner. Res., 23(2)*:205-14, 2008.

Ross, A. H.; Jantz, R. L. & McCormick, W. F. Cranial thickness in American females and males. *J. Forensic Sci., 43(2)*:267-72, 1998.

Ruff, C. B. Age differences in craniofacial dimensions among adults from Indian Knoll, Kentucky. *Am. J. Phys. Anthropol., 53(1)*:101-8, 1980.

Smith, R. W. Jr. & Walker, R. R. Femoral expansion in aging women: implications for osteoporosis and fractures. *Science, 145(3628)*:156-7, 1964.

Syed, F. A. & Ng, A. C. The pathophysiology of the aging skeleton. Curr. *Osteoporos. Rep., 8(4)*:235-40, 2010.

Takahata, Y.; Koyama, N. & Suzuki, S. Do the old aged females experience a long post-reproductive life span?: The cases of Japanese macaques and chimpanzees. *Primates, 36(2)*:169-80, 1995.

Tallgren, A. Neurocranial morphology and ageing--a longitudinal roentgen cephalometric study of adult Finnish women. *Am. J. Phys. Anthropol., 41(2)*:285-94, 1974.

Tigges, J.; Gordon, T. P.; McClure, H. M.; Hall, E. C. & Peters, A. Survival rate and life span of rhesus monkeys at the Yerkes regional primate research center. *Am. J. Primatol., 15(3)*:263-73, 1988.

Torimitsu, S.; Nishida, Y.; Takano, T.; Koizumi, Y.; Makino, Y.; Yajima, D.; Hayakawa, M.; Inokuchi, G.; Motomura, A.; Chiba, F.; *et al.* Statistical analysis of biomechanical properties of the adult skull and age-related structural changes by sex in a Japanese forensic sample. *Forensic Sci. Int., 234*:185.e1-9, 2014.

Van Minh, N. & Hamada, Y. Age-related changes of sulcal imprints on the endocranium in the Japanese macaque (*Macaca fuscata*). *Am. J. Phys. Anthropol., 163(2)*:285-94, 2017.

Van Minh, N.; Mouri, T. & Hamada, Y. Aging-related changes in the skulls of Japanese macaques (*Macaca fuscata*). *Anthropol. Sci., 123(2)*:107-19, 2015.

Walker, M. L. & Herndon, J. G. Menopause in nonhuman primates? *Biol. Reprod., 79(3)*:398-406, 2008.

Walker, M. L. Menopause in female rhesus monkeys. *Am. J. Primatol., 35(1)*:59-71, 1995.

Wang, Q.; Dechow, P. C. & Hens, S. M. Ontogeny and diachronic changes in sexual dimorphism in the craniofacial skeleton of rhesus macaques from Cayo Santiago, Puerto Rico. *J. Hum. Evol., 53(4)*:350-61,s 2007.

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