Measurement of Skull Size on Computed Tomography Images for Developing a Bone Conduction Headset Suitable for the Korean Standard Head Size

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Measurement of Skull Size on Computed Tomography Images for Developing a Bone Conduction Headset Suitable for the Korean Standard Head Size

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감사의 글

논문이 완성되기까지 도움을 아끼지 않고 베풀어 주셨던 모든 분들께 감사의 마음을 전합니다.

먼저 저의 대학원 석사과정에 있어 시작과 완성에 이르기까지 누구보다 깊은 관심과 열정으로 지도해주신 서영준 지도교수님께 진심으로 감사드립니다. 논문 심사 과정에서 아낌없는 조언으로 많은 가르침을 주신 이은정 교수님, 공태훈 교수님께도 깊은 감사를 드립니다. 늘 많은 가르침을 주시고 저에게 귀감이 되는 박동준 교수님, 박상유 교수님, 이소윤 교수님, 이재우 교수님께 감사드립니다.

마지막으로 언제나 저의 학업에 지원과 격려를 아끼지 않고 응원해주시는 부모님과 언제나 마음속 든든한 울타리가 되어주는 아내 김화정, 또한 사랑하는 아들 도윤과 딸 연진이와도 기쁨을 함께 나누고 싶습니다.

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Abstract

Measurement of Skull Size on Computed Tomography Images for Developing a Bone Conduction Headset Suitable for the Korean Standard Head Size

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We aimed to measure the head dimensions on computed tomography (CT) images, to compare them to directly measured head dimensions, and to predict a new parameter of bone thickness for aiding bone conduction implant (BCI) placement.

We reviewed the facial and mandibular bone CT images of 406 patients. Their head sizes were analyzed using five parameters included in the 6th Size Korea project, and they were divided into age groups (ranging from the 10s to the 80s). We compared the head length, head width, sagittal arc, bitragion arc, and head circumference in the CT and Size Korea groups. We also added the parameter bone thickness for aiding BCI placement.

All the head size parameters measured using CT were significantly smaller than those measured directly, with head length showing the smallest difference at 7.85 mm. The differences in the other four parameters between the two groups according to patient age were not statistically significantly different. Bone thickness had the highest value of

4.89±0.93 mm in the 70s and the lowest value of 4.10±0.99 mm in the 10s. Bone thickness also significantly correlated with head width (p=0.038).

Our findings suggested that the CT and direct measurements yielded consistent data. Moreover, CT enabled the measurement of bone sizes, including bone thickness, that are impossible to measure directly. CT measurements may complement direct measurements in the Size Korea data when used for developing bone conduction hearing devices (BCIs and headsets) for the Korean population.

Key words: Bone conduction implant · Headset · Size Korea · Computed tomography · Temporal bone.

I. Introduction

Bone conduction hearing aids can transmit sound vibrations directly to the inner ear through the skull, thereby bypassing any conductive impairment in the external or middle ear [1]. Patients with recurrent otitis media or otitis exacerbation find it difficult to wear conventional air-conduction hearing aids. Moreover, compared to bone conduction implants (BCIs), conventional hearing aids have disadvantages such as the damping of sound vibrations by the hearing aid and the inconvenience due to irritation of the attachment area. BCIs are good alternative options for these patients [2,3]. Since the successful placement of the first implant was reported in 1977, more than 10,000 patients worldwide have received BCIs [1]. In addition, conventional bone conduction hearing aids, such as the soft Headband, are a gold standard for preoperative evaluation in young patients who cannot undergo implantation and are used as a good method for hearing rehabilitation in patients refusing surgery [4,5].

To maximize the gain of sound conduction, the bone conduction vibrator should be kept under a constant pressure (approximately 2-5 N) on the head [6]. The shape of the headset body determines the degree of contact and pressure between the head and the device, and it plays an important role in the efficacy of sound transmission. Although many bone conduction hearing aids have been developed and used, most of them are foreign products designed for different populations; hence, they are not suitable for the heads of Korean adults. Studies have also shown that, compared to the Caucasians, Asians have heads that are more round, with flatter foreheads and backs [7]. Therefore, products designed using different population data may not be suitable for Koreans.

The human body measurement research project for Koreans is currently in progress and in its 7th stage. This project has yielded useful data for designing products and devices in various medical fields. However, among the Korean human body measurements, the head size measurements may present some limitations. The head size was mainly measured in people aged less than 69 years old, with relatively less data being collected from the elderly.

Moreover, the project determined the size of the head by using five criteria, which did not account for the actual wearing position of the bone conduction headset. Furthermore, the thickness of the temporal bone to which the BCI was applied to could not been determined.

Human anthropometric measurements determined using computed tomography (CT) images have been reported in various studies [8]. In particular, CT enables the measurement of any diameter of the skull bones that cannot be measured directly. In this study, we measured the head dimensions on CT im- ages and compared them to direct measurements of the human head. We aimed to supplement existing head size data with data from our analyzed parameters on CT images and to predict a new parameter of bone thickness for aiding BCI placement.

II. Subjects and Methods

A. Patients

This study was performed at Wonju Severance Christian Hospital and was approved by the Institutional Review Board (CR318037). Facial and mandibular bone CT images of patients acquired between January 1, 2017 and July 1, 2018 were reviewed. The patients' age at the time of acquiring the CT images had to range from 10 to 90 years old, because we aimed to classify the head sizes according to the ages ranging from the 10s to the 80s.

The exclusion criteria were as follows: 1) images that did not include a vertex and could not be used to measure the skull size; 2) patients with a past history of conditions affecting skull size measurement, e.g., skull fracture or brain surgery; and 3) patients without clinical data such as weight and height. Finally, we enrolled 406 patients in this study. The age of the patients ranged from 10 to 88 years, and their mean age was 48.58±22.24 years. Of the 406 patients, 221 (54.4%) were males and 185 (45.6%) were females. Patients were divided into groups according to age and included 42 to 63 people in each group (10-19, 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, and 80-89).

The 6th Size Korea project included measurements from 14,016 people (7,532 males and 6,484 females) aged 7 to 69 years old, whose head size parameters were directly measured. Using propensity score matching, considering the height and weight of the experimental group, we were able to select 1,218 matched individuals, i.e., three times the number of patients with CT data.

B. Measurements in the Size Korea project

The 6th Size Korea project included five parameters related to skull size, namely, head length, head width, sagittal arc, bitragion arc, and head circumference. The definitions of the measurement parameters and the measurement reference points are summarized in Table 1.

Table 1. Definition of head size parameters in the Size Korea project and in CT images

Parameter	Definition in the Size Korea project	Definition in the CT images
Head length	The distance from the glabella to the occiput	The distance from the eyebrow to the protruding point on the posterior head along the highest plane of the nose
Head width	The horizontal distance between the right and left euryon	The horizontal distance from the plane where the point near the left head protrudes the most
Sagittal arc	The length from the glabella to the inion	The distance from the eye to the point at the back of the head through the nose along the highest plane of the nose
Bitragion arc	The length from the right tragion, passing the vertex, to the left tragion	Length from the plane of the ear canal to the plane of the opposite ear canal (2-3 planes behind the ear ball)
Head circumference	The perimeter through the glabella and the occiput	Head circumference from the plane where the head protrudes the most
Bone thickness	-	The thickness of the temporal bone measured at a point 3 cm posterior and 2 cm superior to the posterior wall of the EAC

CT, computed tomography; EAC, external auditory canal

Two experimenters were trained to become accustomed with the measurement tools and procedures. The features were initially identified as skeletal landmarks on the face. Measurements were obtained to the nearest millimeter and were recorded in centimeters. Normally, the investigators worked in a private room to provide the subject the most preferable environment. All subjects were provided a non-disclosure agreement to preserve their names.

C. Measurements on the CT images

Facial and mandibular bone CT was performed using GE Light Speed Pro 16 (GE, Milwaukee, WI, USA) and Philips Brilliance 64 (Philips, Cleveland, OH, USA) (thickness, 2.5 mm). The patients underwent axial topography parallel orbito-meatal line scanning in the normal supine position. Coronal and sagittal images were reconstructed perpendicular to the orbital plane and perpendicular to the axial plane, respectively.

The five skull-size-related parameters were measured on facial and mandibular bone CT images. We additionally measured temporal bone thickness, which could not be directly measured. Temporal bone thickness was measured at a point 3 cm posterior and 2 cm superior to the posterior wall of the external auditory canal (EAC), which is the typical location of BCI placement. These measurements were performed by two separate researchers. The lengths of straight-line parameters (head length, head width, and thickness) were measured using the Centricity software (Centricity; GE Medical Systems, Milwaukee, WI, USA), and the lengths of curved parameters, such as head circumference, bitragion arc, and sagittal arc, were measured using Image J (National Institutes of Health, Bethesda, MD, USA). The measurements were based on the bone rather than the soft tissue.

Table 1 lists the definitions and reference points of the parameters used in the CT image measurements. Fig. 1 provides an example of parameter measurements on CT images and direct measurements.

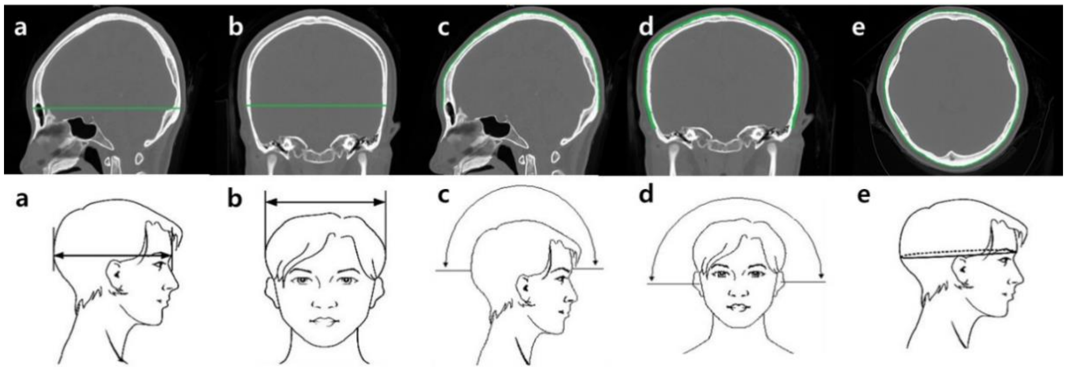

Fig. 1. Illustration of the measurement of head length (A), head width (B), sagittal arc (C), bitragion arc (D), and head circumference (E). We used the Image J program and Centricity web program to measure the lengths on the computed tomography (CT) images. However, the CT measurements were based on the bone rather than the soft tissue

D. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 23.0 (IBM Corp., Armonk, NY, USA). Propensity score matching was performed, and a 1:3 ratio matching (CT group:Size Korea group) was done considering the height, weight, and body mass index of the CT group. A paired t-test was performed to analyze the two groups. A p-value less than 0.05 was considered to indicate a significant difference.

III. Results

The measured head size parameter values are provided in detail in Table 2. The head size parameter values measured on CT images were significantly smaller than those measured directly on the human body. The average difference was the greatest for head circumference at 49.5 mm (552.45±13.17 mm in the Size Korea measurement and 502.80±24.26 mm in the CT measurement; $p<0.001$), and it was the smallest for head length at 7.85 mm (178.42±6.21 mm in the Size Korea measurement and 170.86±8.30 mm in the CT measurement; $p<0.001$).

Table 2. Comparison of head size parameter values between the Size Korea project and CT images

Measure	Values in the Size Korea project (n=1218)	The values in the CT images (n=406)	p-value
Head length	178.42 ± 6.21	170.86 ± 8.30	<0.001
Head width	153.20 ± 5.89	144.56 ± 6.66	<0.001
Sagittal arc	329.10 ± 17.48	297.84 ± 18.06	<0.001
Bitragion arc	363.53 ± 12.38	319.15 ± 23.39	<0.001
Head circumference	552.45 ± 13.17	502.80 ± 24.26	<0.001

Values are presented as mean±standard deviation unless otherwise indicated. CT: computed tomography

The differences in four parameters (except for head length) between the two groups according to the age groups were not statistically significantly different. The changes in head size parameters measured on CT images according to the age groups are presented in Table 3. The relationship between the Size Korea project's directly measured data and CT data according to the age groups is shown in Fig. 2. This implied that all measurements, excluding the soft tissues, performed in the Size Korea project were consistent with the measurements we performed on CT images. The head lengths measured on CT images in young patients (ages in the 10s and the 20s) were considerably larger than those in the Size Korea data. This could be because in the Size Korea data, the measurements of human body size showed a steep increase until the 20s, showing the highest values, but gradually decreased thereafter from the 30s.

Table 3. Changes in head size parameter values in the CT images according to patient age

Age	Head length	Head width	Sagittal arc	Bitragion arc	Head circumference	Bone thickness
10s	179.50±8.43	146.53±5.58	298.21±20.09	335.39±17.44	509.35±23.40	4.10±0.99
20s	174.81±8.28	146.47±6.44	302.14±19.44	328.81±20.13	510.52±25.00	4.13±0.88
30s	170.99±7.63	145.38±7.54	293.36±14.34	321.30±22.13	507.99±17.43	4.14±1.10
40s	170.79±7.23	142.67±6.84	296.77±17.65	315.93±19.95	502.73±17.61	4.58±0.78
50s	165.36±6.64	140.76±6.73	294.60±15.71	315.71±37.09	486.80±28.98	4.24±1.28
60s	168.73±9.09	144.40±4.82	295.19±22.06	307.41±17.93	497.16±18.42	4.21±0.95
70s	170.68±8.05	141.25±6.39	304.24±13.88	312.02±14.08	504.15±14.87	4.89±0.93
80s	168.68±7.39	144.56±6.66	298.70±17.13	303.37±12.95	495.35±32.56	4.74±0.97

Values are presented as mean±standard deviation. CT: computed tomography

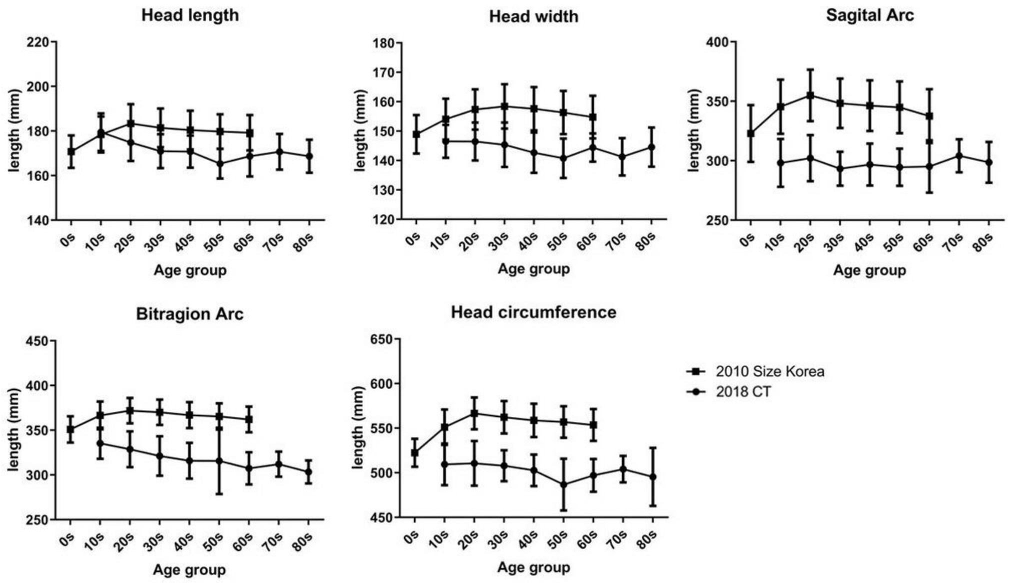

Fig. 2. Changes in head size parameters (A–E) according to ages from 10 years to 80 years. CT: computed tomography.

We measured temporal bone thickness for aiding BCI placement by using CT data, because it cannot be directly measured using the Size Korea data. Bone thickness is an important fac- tor that determines the benefit of sound gain as well as the surgical indication for BCI placement. The highest value was 4.89±0.93 mm in the 70s and the lowest value was 4.10±0.99 mm in the 10s (Table 3). Correlation analysis (Fig. 3) was performed between the five head size parameters and temporal bone thickness, and only head width showed a significant correlation (r2=0.204, p=0.038).

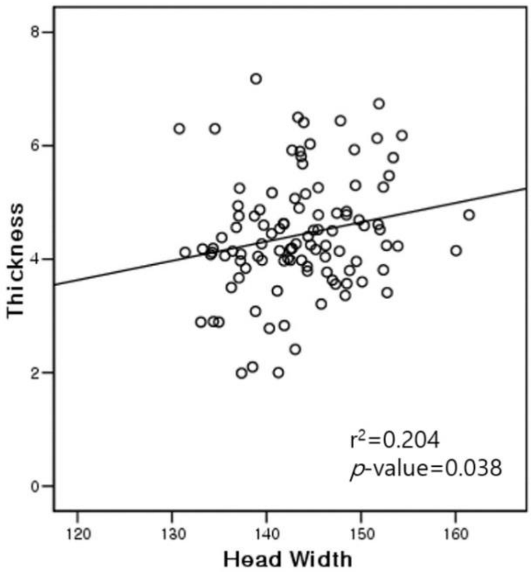

Fig. 3. The correlation between bone thickness (mm) and head width (mm). Bone thickness increased with an increase in head width.

IV. Discussion

Bone conduction hearing aids transmit sound vibrations through the skin to the skull bone, and further to the cochlea in the inner ear, bypassing any conductive impairment in the external or middle ear [9,10]. Therefore, bone conduction hearing aids or headsets are an option for treating deafness. Recently, non-invasive bone conduction hearing aids, such as the Baha SoundArc (Cochlear, Sydney, Australia) and Adhear (MED-EL, Innsbruck, Austria), have been designed to be placed over the ears and be worn behind the head [2,11]. SoundArc demonstrated equal performance to the Softband and superior performance to the Headband and Testband [12]. The performance of nonsurgical bone conduction solutions relies mainly on two factors: sound transfer efficiency and minimizing feedback. To solve these problems, bone conduction devices should be attached to the mastoid area with appropriate pressure to transmit the sound, and the contact force should be about 2-5 N [6]. Bone conduction devices should be fixed without any gaps at the attachment site; otherwise, they will have a negative impact on sound transmission. Head size is an important point to consider when developing devices such as bone conduction headsets and hearing aids. Most bone conduction devices are designed using reference standards obtained from foreign patient populations. Therefore, such devices may not have the maximum efficiency when used in Korean patients with different head sizes. Therefore, to develop a product suitable for Koreans, the establishment of a reference standard for the Korean head size is pertinent. Although the Size Korea project provides head size data, these are not widely used because they have limited applicability when developing medical devices. Temporal bone thickness data should be obtained to plan the position of BCIs and accomplish a successful surgery.

Anthropometric data are important factors in the design of medical devices. However, in reality, head and face shapes differ between individuals of different nationalities. Therefore, it is imperative to consider these differences in areas of object, system, and environmental design. Few studies have calculated the Korean head size. A single photon emission CT study on children suggested a series of Korean computational head phantoms with detailed cranial substructures [13]. Lee, et al. [5] showed that the face and head sizes of Korean male and female individuals have more statistically significant morphological differences than do those of Japanese individuals. Since 2003, the Korean anthropometric data survey project named Size Korea has provided Korean body size reference data, including head size data. Knowledge of the human head form is essential in a variety of fields like design and medicine [7,14]. However, the Size Korea project included only five head size parameters, which limited their applicability when designing medical devices, especially BCIs.

We thought that the measurement of head size on CT images could provide additional reference data to complement the Size Korea project's anthropometric data, and hence, we compared the head size data measured on CT images to those directly measured for the Size Korea project. In this study, the values measured on CT images were lower than the corresponding Size Korea values. We think that the CT values were lower because 1) we measured the size of the bone rather than the soft tissue and 2) the measurement points were not exactly identical between the two measurement groups; moreover, errors may have occurred during the measurements. Although the measured CT values were smaller, the five head size parameters in both the groups showed a similar tendency when viewed on the numerical graph based on the age groups. The observation of a similar tendency according to the age groups shows the reliability of the CT measurement method.

We think that CT measurements have some strengths over direct measurements. CT enables the measurement of bone sizes that are impossible to measure directly. This would be meaningful when designing bone conduction devices, which should have a contact with appropriate pressure on the bone. In addition, we could obtain and include data from patients in their 70s and 80s, and could determine new parameters such as temporal bone thickness without re-imaging [15]. Therefore, if sufficient CT data are available in the future, they could complement national reference data (such as the Size Korea data) when developing bone conduction devices for the Korean population. A limitation of this study was that most of the patients with CT data were from the Chungbuk or Gangwon provinces. Therefore, these patients are not representative of the whole Korean population. However, there is no evidence showing that head size changes in different regions of Korea. Therefore, we think these data can serve as meaningful standards for the Korean population.

The position of bone conduction devices is important, because it plays a role in sound transmission. According to the literature, the proximity of a bone conduction device to the cochlea is important in improving the amplification of the signal provided to the cochlea [16]. Simultaneously, avoiding the sigmoid sinus can prevent bleeding and epidural hematoma [17]. In this study, we measured temporal bone thickness at a point 3 cm posterior and 2 cm superior to the posterior wall of the EAC, where BCIs are usually placed [18]. The mean thickness ranged from 4.10±0.99 mm to 4.89±0.93 mm, showing sufficient depth for BCI placement. The correlation between the five parameters and temporal bone thickness showed that bone thickness increased only with an increase in head width ($r2=0.204$, $p=0.038$).

V. Conclusion

In conclusion, the CT-based measurement method described here may help uncover important predictive factors through modeling, and it may be useful for analyzing not only bone thickness but also other important parameters. If more CT data are accumulated in future studies, they could be used in studies to identify numerical associations between head size parameters and to develop predictive factors for specific items (e.g., temporal bone thickness). Moreover, when used together with the Size Korea data, our CT data will aid the development of specific bone conduction headsets for Koreans.

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국 문 요 약

컴퓨터 단층 촬영 영상을 통한 두개골 크기 측정:
한국 표준 머리 크기에 적합한 골전도 헤드셋 개발을 위하여

골전도 보청기는 소리 진동을 두개골을 통해 내이로 직접 전달하여 기존 보청기 착용이 힘들거나, 한쪽의 완전 청력소실이 있는 환자에서 유용하게 사용된다. 소리 이득을 최대화하기 위하여 골전도 진동기가 머리에 일정한 압력을 가하는 것이 중요하다. 이를 위하여는 한국인의 머리 크기에 맞는 보청기의 개발이 필요하며, 한국인의 정확한 머리 크기를 파악하는 것이 중요하다. 한국인구를 대상으로 한 대규모 인체 측정 연구 프로젝트 자료가 있으나(사이즈 코리아 프로젝트), 고령자의 데이터가 적고 골전도 임플란트에서 중요한 측두골의 두께를 측정하지 못하는 단점이 있다. 이번연구에서 저자는 CT 이미지를 통하여 두개골의 크기를 측정하여 사이즈 코리아의 직접 측정값과 비교 분석하여 CT 측정값의 신뢰성을 보고, CT 를 통한 측두골 측정값을 다른 항목과의 관계를 보고자 하였다.

우리는 6 차 사이즈 코리아 프로젝트에서 측정한 머리크기의 5 가지 항목(머리 두께, 머리 너비, 머리 둘레, 눈살 뒤통수 길이, 귀구슬 사위 위 거리)을 406 명의 안면골 CT 에서 측정하였으며, 측두골의 두께를 추가로 측정하였다. 이후 사이즈 코리아 프로젝트의 값과 CT 를 통하여 측정한 값을 나이대별로 나누어 비교 분석하였다(10 대에서 80 대까지).

모든 머리 크기 항목에서 CT 측정값이 직접 측정값보다 작게 나왔으며, 그 중에서 머리 두께가 7.5mm 로 가장 적은 차이를 보였다. 연령대별로 머리 크기 항목을 비교하였을 때에도 마찬가지로 CT 측정값이 작게 나왔으나, 연령대별로 증가와 감소의 경향이 비슷함을 확인할 수 있었다. 측두골 두께는 70 대에서

4.89±0.93mm 로 가장 두꺼웠으며 10 대에서 4.10±0.99mm 로 가장 가늘었다. 측두골 두께는 머리 너비와 통계적으로 유의하게 상관성을 보였다 (p=0.038) .

이번 연구에서 CT 측정값과 사이즈 코리아 측정값들은 비교적 일관된 변화를 보였다. 또한 CT 는 뼈 두께를 포함하여 직접 측정할 수 없는 뼈 크기를 측정할 수 있었다. CT 를 통한 머리 크기의 측정은 이처럼 머리 사이즈의 직접 측정값들을 보완할 수 있으며, 추후 많은 데이터들이 쌓였을 때 한국인을 위한 골전도 기기들을 개발하는데 또 하나의 참조 데이터로도 사용할 수 있을 것이라 생각한다.

핵심되는 말: 골전도 임플란트, 헤드셋, 사이즈 코리아, 컴퓨터 단층촬영, 측두골