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Title Page

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Title: Operative simulation of anterior clinoidectomy using rapid prototyping model molded by a three-dimensional printer.

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Abstract

[Background] Since the anatomical three-dimensional (3D) positional relationship is complex around the anterior clinoid process (ACP), experience of many surgeries is necessary to understand anterior clinoidectomy (AC). We prepared a 3D synthetic image from computed tomography angiography (CTA) and magnetic resonance imaging (MRI) data and a rapid prototyping (RP) model from the imaging data using a 3D printer. The objective of this study was to evaluate anatomical reproduction of the 3D synthetic image and intraosseous region after AC in the RP model. In addition, the usefulness of the RP model for operative simulation was investigated.

[Methods] The subjects were 51 patients examined by CTA and MRI before surgery. The size of the ACP, thickness and length of the optic nerve and artery, and intraosseous length after AC were measured in the 3D synthetic image and RP model, and reproducibility in the RP model was evaluated. In addition, 10 neurosurgeons performed AC in the completed RP models to investigate their usefulness for operative simulation.

[Results] The RP model reproduced the region in the vicinity of the ACP in the 3D synthetic image including the intraosseous region at a high accuracy. In addition, drilling of the RP model was a useful operative simulation method of AC.

[Conclusions] The RP model of the vicinity of ACP prepared using a 3D printer showed favorable anatomical reproducibility including reproducing the intraosseous region. In addition, it was concluded that this RP model is useful as a surgical education tool for drilling.

Key word: 3D printer, operative simulation, rapid prototyping model, anterior clinoidectomy, surgical training

Text:

Introduction

The anterior clinoid process (ACP) is surrounded by the internal carotid artery (IC), superior orbital fissure (SOF), optic nerve, and cavernous sinus, being anatomically complex[3,19)]. Anterior clinoidectomy (AC) is an important procedure for skull base surgery[10,11,17,19,26)] initially reported by Dolenc et al. in 1985, in which AC was applied to IC-ophthalmic aneurysm through the "combined epi- and sub-dural direct approach[4)]. It is now applied to surgeries of paraclinoid and basilar top aneurysms, skull base tumor, and the cavernous sinus[3,10,11,17,18,19,26)]. In the general procedure of AC, the SOF is drilled from the lateral toward the medial side, the optic canal is unroofed, egg-shell-shaped drilling is applied to the inner ACP, and the optic strut, which is the base of the ACP, is finally cut to complete the procedure[10,11,17,18,19,26)]. In AC, there is a risk of directly damaging the optic, oculomotor, and trochlear nerves and ophthalmic nerve of the trigeminal nerve, and causing various complications, such as IC injury and cerebrospinal rhinorrhea[10,11,17,18,19)]. Therefore, for neurosurgeons, sufficient preoperative simulation and improvement of the surgical procedure are necessary[7)]. Generally, when young neurosurgeons learn difficult surgeries including AC, they refer to texts and videos of surgeries. However, it is difficult to understand the three-dimensional (3D) anatomical structures in the surgical field using these methods alone, and they cannot experience bone drilling[5)]. Cadaver dissection is a basic educational method necessary to learn 3D anatomy[2,13)]. It is also very useful for surgeons to understand drilling of actual bone and surgical approaches, but cadaver dissection is limited by legal ethics, and surgeons cannot frequently perform it[2,13]. With recent modification and improvement of the performance of computed tomography (CT), magnetic resonance imaging (MRI) and 3D digital subtraction angiography (DSA) as medical test equipment and a 3D image-analysis software as peripheral devices, rapid prototyping (RP) models prepared using a 3D printer has become utilized for preoperative simulation and surgical training[5,7,8,9,12,14,23].

We prepared a 3D synthetic image of the vicinity of the ACP including the optic nerve and IC from images of CT angiography (CTA) and MRI, which are common preoperative examinations, and prepared an RP model based on the imaging data using a 3D printer. The objective of this study was to evaluate anatomical reproducibility of the 3D synthetic image and intraosseous region after AC in the RP model. In addition, the usefulness of the RP model for operative simulation was investigated.

Methods and materials

Patient population

Of patients treated at the Department of Neurosurgery, Toho University Omori Medical Center between February 2012 and February 2016, 51 consecutive patients examined by CTA and MRI before surgery were selected for the subjects. No cases of emergency surgery were included, and all cases were scheduled surgical patients. The mean age was 55.5 years old (26-82 years old), and 27 and 24 patients were male and female, respectively. The disease was meningioma in 18, glioma in 13, metastatic brain tumor in 6, pituitary tumor in 3, acoustic tumor in 2, epidermoid in 2, arteriovenous malformation in 1, brain abscess in 1, vertebral artery dissection in 1, germinoma in 1, craniopharyngioma in 1, malignant lymphoma in 1, and hemangiblastoma in 1. The lesion was located in the vicinity of the ACP in 11, and it was sphenoid-ridge meningioma in 4, pituitary tumor in 3, epidermoid in 1, craniopharyngioma in 1, olfactory groove meningioma in 1, and orbital tumor in 1.

Preparation of 3D synthetic image

The CT device used was 64-row x 2 multi-detector CT (SOMATOM Definition Flash, SIEMENS, Munich, Germany). For the MRI device, 1.5T MRI (Excelart Vantage MRT-2003/P3: Toshiba, Tokyo, Japan) was used.

3D synthetic images were prepared using an integrated medical image system (SYNAPSE VINCENT: Fuji Film Co., Tokyo, Japan). Digital imaging and communications in medicine (DICOM) data of CT and MRI were transferred online to the integrated medical image system. For image registration, the auto registration function based on normalized mutual information attached to the integrated medical image system was used. The CTA images of the skull and artery and MRI of the optic nerve were extracted by thresholding.

RP model-molding method

DICOM data format was converted to Standard triangulated language (STL) data format on the integrated medical image system and sent to a computing system for 3D molding (Geomagic Freeform, 3D Systems Co., SC, USA).

A RP model was prepared from the STL data on the computing system for 3D molding using a binder jetting 3D printer (Z Printer® 450: 3D Systems Co., SC, USA). The molding method employed by this 3D printer was the powder lamination method with binder jetting. In this method, material powder, mainly comprised of plaster (zp®150 powder, 3D Systems Co., SC, USA) is laminated every 0.1 mm and molded by solidifying with a binder (zb®63 Clear, 3D Systems Co., SC, USA). For coloring, a completely automatic full color ink-jet system (hp 11, Hewlett Packard Co., CA, USA) was used. The RP model immediately after molding was buried in the white material powder in the device. The adhering excess powder was removed using an exclusive air spray. Finally, the model was coated with an exclusive wax mainly comprised of heated liquid paraffin to increase the physical strength. When the exclusive wax was excessively applied, it was melted and removed using a heat gun (Hakko heating gun 882: Hakko Co., Osaka, Japan). The resolution of this 3D printer was 300 x 450 dots per inch (dpi) and the minimum feature size was 0.15 mm.

Evaluation of anatomical reproducibility in RP model

Firstly, the anatomical distances described below were measured in the 3D synthetic image using software attached to the integrated medical image system. Then, these distances were similarly measured in the RP model of the same case (Fig. 1 A-D). The distances in the RP model were measured using a divider [83A-4 “Yankee” Spring-Type Dividers (150 mm), the L.S. Starrett Co., MA, USA], which is a compass with needle tips on both legs for drawing. The needle tips of the both legs of the divider were set at the 2 ends of the target distance, and the distance was measured using a digital caliper (Shinwa rules digital caliper model 19975, Shinwa rules Co., Niigata, Japan). The anatomical distances were compared between those measured in the 3D synthetic image and RP model (Table 1 a-l).

Evaluation of anatomical reproducibility of intraosseous region in RP model

Bone was drilled in the order of ‘m’ to ‘o’ in the 3D synthetic image and the intraosseous anatomical distances were measured (Table 1). AC in the 3D synthetic image was performed using the partial image cut tool equipped in the integrated medical image system. Then, the RP model of the same case was similarly drilled using a drill for practice of surgery (OsseoDoc boorsysteem, Bien Air co., Switzerland), and the intraosseous anatomical distances were measured using the divider and digital caliper (Fig. 1 E-H). The distances were compared between those in the 3D synthetic image and RP model (Table 1 m-p).

Accuracy of lesions in the vicinity of the ACP in RP model

The lesions were divided into 2 groups based on their location: lesions located in the vicinity of the ACP (16 sides) (the lesion had expanded toward the bilateral sides in 3 cases of pituitary tumor and one case each of craniopharyngioma and olfactory groove meningioma) and those located outside the vicinity of the ACP (86 sides) (Fig. 2 A-C). Errors and reproducibility of the items ‘a’ to ‘p’ in the RP model were evaluated in each group (Table 1). The errors were calculated using the formula below:

Error (%) = {(value measured in RP model) - (value measured in 3D synthetic image)}/(value measured in 3D synthetic image) x 100

Operative simulation using RP model

Ten neurosurgeons performed AC using one of the RP models of the most favorably reproduced cases. Ten neurosurgeons were 6 board certified neurosurgeons and 4 non - certified neurosurgeons, respectively. Firstly, the SOF, optic canal, ACP, foramen rotundum, foramen ovale, optic nerve, optic chiasma, IC, M1, and A1 were selected for the anatomical evaluation items, and identification of these was evaluated using a 4-step grading system (4. Clearly identifiable, 3. Identifiable, 2. Difficult to identify, 1. Not identifiable). For the evaluation items of the intraosseous region after AC, the optic nerve, IC, and optic strut were selected, and the grade of identification of these was similarly judged. In addition, similarity to the human bone (4. Very similar, 3. Similar, 2. Not very similar, 1. Not similar) and the usefulness as a model for drilling (4. Very useful, 3. Useful, 2. Fair, 1. Not useful) were evaluated.

In statistical analysis, the paired t-test was used to analyze the anatomical reproducibility in the RP model. For the accuracy of lesions in the vicinity of ACP in the RP model, the unpaired t-test was used. $p<0.05$ was regarded as significant. For evaluation of operative simulation of AC using the RP model, intraclass correlation coefficients (ICC) were used (IBM SPSS Statistics, ver.19, IBM Co., NY, USA).

This study was approved by the Ethics Committee of School of Medicine, Faculty of Medicine, Toho University (approval number: 27074).

Results

The RP models of the 51 cases (102 sides) were prepared. The reproducibility of the anatomical structures was 91-98% (Table 1, 2). Of the anatomical length items ‘a’ to ‘d’, which measured the length of the bone from the tip of the SOF, a significant error was noted only in ‘c’. In ‘e’ to ‘l’, which measured the thickness of the arteries, optic nerve and bone, errors were noted in 6 of the 8 items (Table 1, 2). In ‘m’ to ‘p’ representing the length after bone drilling, a significant difference was noted only in ‘o’ out of the 4 items (Table 1, 2). On comparison between the groups with a lesion in and outside the vicinity of the ACP, no error was noted in any of the items from ‘a’ to ‘p’ (Table 1, 3). No significant difference was detected in the reproducibility between the groups ($p=0.17$) (Table 1, 3). On evaluation of operative simulation using the RP model by neurosurgeons, ICC of anatomical identification of each region and those of the intraosseous regions after AC were high (0.93 or higher) (Table 4).

Discussion

Securing the accuracy of RP models molded using a 3D printer forms the basis of preoperative simulation and surgical training. Operations producing an error in the accuracy in the RP model preparation process from the image data include registration of medical images of different modalities, conversion of data format, and molding of the RP model[1,6,8,15,16,25)]. Firstly, in registration of medical images of different modality, CT and MRI data were automatically registered based on normalized mutual information[16,25)]. This method is employed by many image processing software for medical use, and it is incorporated in planning of cyber knife treatment because of its high accuracy of image registration. Therefore, image registration may be unlikely to influence the accuracy of RP models. Secondly, conversion of data format may have an influence. STL data format is used in 3D printers, and conversion of DICOM data format used for medical image data is necessary[6,8,15)]. STL data format is a system expressing 3D shapes as aggregations of small triangles and accurate expression of curved lines and surfaces is difficult. Thus, when images visualized in DICOM data format are converted to STL data format, minute shapes are likely to be broken or lost[8)]. Moreover, the window width and level and image threshold set in DICOM data format are initialized when the format is converted to STL data format, and resetting is inevitably necessary[1,6,8)]. To minimize data format-associated errors, DICOM data format was converted to STL data format while the measure and values were left on the format immediately before conversion, which resulted in fewer measurement errors in the anatomical length and intraosseous length after AC between the 3D synthetic image and RP model, suggesting that the accuracy as an RP model for surgical simulation was retained. Errors were likely to be produced in the thickness of blood vessels and nerves as previously reported, and these remain to be solved[8)]. Thirdly, errors are produced in the RP model molding process. Unlike 3D synthetic images, consideration of the physical characteristics is necessary for RP models. In completed RP models, thin blood vessels and processes are very fragile and easily broken by an air spray. Moreover, as observed in this study, blood vessels and nerves in the RP model are thicker than those in the image, and visibility of small holes, such as the foramen rotundum, decreases. Insufficient removal of the material powder and excess coating with the exclusive wax are considered the causes[8)].

It has been pointed out that the ability of visualizing the optic nerve and optic canal is likely to decrease in lesions in the vicinity of the ACP on neuroradiology imaging. It is considered that since brain tumor compresses for a prolonged period and thins the optic nerve, deforming the optic canal, the ability of visualizing these decreases[20,24)]. Especially, as the optic nerve is poorly visualized on MRI in meningioma present in the vicinity of the ACP compared with other brain tumors[20)]. Many cases of meningioma show an iso-intensity similar to the intensity of the optic nerve on T1-weighted imaging and this is considered one reason[20)]. In our study, the anatomical length and thickness measured in the CTA-and MRI-based RP models of cases with a lesion present in the vicinity of the ACP were not different from those in the RP models of cases with a lesion located outside the vicinity of the ACP, suggesting that this RP model is useful as a model for AC for lesions located in the vicinity of ACP. Although no significant difference was noted, the reproducibility of the optic canal was 95% in the RP models of cases with a lesion present outside the vicinity of the ACP but 67% in the models with a lesion in the vicinity of the ACP, to which attention should be paid in molding an RP model of lesions.

In addition, if the IC and optic nerve are molded with a soft material in the RP model with a lesion in the vicinity of the ACP, there will be better reproducibility of the optic canal. As a result, realistic and haptic sensation are improved, and it will be more useful for surgical simulation and education.

Neurosurgery requires abundant anatomical knowledge and advanced techniques21), for which preoperative simulation and surgical training are important21). Preoperative simulation using a 3D printer as one tool has been reported5,7,8,9,12,14,23). Mashiko et al.12) reported that they prepared a 3D hollow and elastic aneurysm model and performed operative simulation of clipping, and the model was useful to select the optimum clip. Oishi et al.14) reported that they performed simulation of surgery for deep intracranial tumors, which resulted in increases in anatomical understanding of the deep region of the brain and brain tumor excision rate. In addition, Kondo et al.7) proposed mesh patterning of skull base tumors as new devising of molding RP models mainly prepared with plaster, and realized seeing through the eloquent area in the deep region of tumors.

Several studies on RP model prepared using a 3D printer for surgical training have been reported[5,14,22,23)]. Specifically, RP models were useful for training of ventricular drainage and transsylvian approach[5,22)].

Recently, 3D printers using various materials have been developed[7)]. The 3D printer used in our study mainly uses plaster so that drilling is possible. To our knowledge, RP models molded using a 3D printer for training of bone drilling has not previously been reported. On the questionnaire survey of the neurosurgeons, they stated that the model was very similar to human bone as the impression of drilling. In addition, the reproducibility of the intraosseous IC and optic nerve was favorable, suggesting that it has sufficient specifications as a model for surgical training of AC. Regarding points to be paid attention to in drilling of the RP model, plaster shavings may deposit on and hide deep minute anatomical regions. This may have been the cause of reduced visibility of the optic strut in AC.

Once image data of an RP model are input into a 3D printer, the model can be endlessly molded, and this is an advantage of 3D printers. This may prepare an environment allowing repeat practice and lead to smooth learning of surgical procedures.

The RP model, which is formed by combining a hard skull with soft brain tissue or blood vessels, can simulate actual surgery more closely[12,23)]. However, at present, it takes time and effort to create such an RP model. In the future, development of a 3D printer that can easily create an RP model combining bone and soft tissue in a short time is expected. The RP model produced in this study is a model of bone, blood vessels and optic nerve formed by plaster, which has the same hardness, but has the advantage that it can be easily produced in a short time. As a model for drilling, this RP model may be considered sufficient.

Conclusion

The anatomical reproducibility of the vicinity of the ACP including the intraosseous region in the RP model prepared using a 3D printer was favorable. It was concluded that this RP model is useful as a surgical education tool for drilling.

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Compliance with ethical standards

This article does not contain any studies with human participants performed by any of the authors.

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Conflict of interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Figure legends

Figure 1

Rapid prototyping (RP) model and three-dimensional (3D) synthetic image.

RP model: rapid prototyping model,

3D synthetic image: three-dimensional synthetic image

A upper view of RP model,

B upper view of 3D synthetic image,

C right lateral view of RP model,

D right lateral view of 3D synthetic image,

E right upper rear view of RP model after anterior clinoidectomy,

F right upper rear view of 3D synthetic image after anterior clinoidectomy,

G upper view of RP model after anterior clinoidectomy,

H upper view of 3D synthetic image after anterior clinoidectomy

Table 1

Each anatomical distance measured.

SOF: superior orbital fissure,

ACP: anterior clinoid process,

IC: internal carotid artery,

M1: M1 segment of middle cerebral artery,

A1: A1 segment of anterior cerebral artery

As the ACP thickness, the thickest region observed from right beside the anterior cranial base was measured. The thickness of the IC, M1, and A1 arteries was measured at the carotid bifurcation. The optic nerve thickness was measured at the site it came out of the optic canal. Then, bone was drilled in the order of ‘m’ to ‘o’ in the three-dimensional synthetic image, and the intraosseous anatomical distances were measured.

Figure 2

Illustrative case of left sphenoid-ridge meningioma. The photograph showed the rapid prototyping (RP) model molded by the three-dimensional printer.

RP model: rapid prototyping model

A RP model with the tumor. T: tumor, red: artery, yellow: optic nerve.

B RP model without the tumor. The model showed the thickened anterior clinoid process.

C RP model after anterior clinoidectomy. The internal carotid artery and optic nerve were well molded.

Table 2

Comparisons between three-dimensional (3D) synthetic image and rapid prototyping model (RP) model.

RP model: rapid prototyping model,

3D synthetic image: three-dimensional synthetic image,

SD: standard deviation

*: p<0.05, **: p<0.01

Table 3

Comparisons between the vicinity of the anterior clinoid process (ACP) and outside the vicinity of the ACP.

ACP: anterior clinoid process,

SD: standard deviation

Table 4

Operative simulation using rapid prototyping (RP) model.

ICC: intraclass correlation coefficients,

95%CI: 95% confidence interval,

SOF: superior orbital fissure,

OC: optic canal,

ACP: anterior clinoid process,

FR: foramen rotundum,

FO: foramen ovale,

ON: optic nerve,

IC: internal carotid artery,

A1: A1 segment of anterior cerebral artery,

M1: M1 segment of middle cerebral artery,

AC: anterior clinoidectomy

Table 1

a	Distance between the tips of the SOF and ACP
b	Distance between the tip of SOF and lateral side of the optic nerve at the orifice of the optic canal
c	Distance between the tip of SOF and medial side of the optic nerve at the orifice of the optic canal
d	Shortest distance between the tip of SOF and foramen ovale
e	ACP thickness
f	IC thickness
g	M1 thickness
h	A1 thickness
i	Optic nerve thickness (transverse diameter)
j	Optic nerve thickness (longitudinal diameter)
k	Size of the orifice of the optic canal (transverse diameter)
l	Size of the orifice of the optic canal (longitudinal diameter)
m	The anterior cranial base was drilled from the tip of the SOF toward the medial right side, and the distance to the lateral margin of the optic nerve was measured.
n	The anterior cranial base was drilled from 5 mm posterior to the tip of the SOF toward the medial right side, and the distance to the lateral margin of the optic nerve was measured.
o	The anterior cranial base was drilled from 10 mm posterior to the tip of the SOF toward the medial right side, and the distance to the lateral margin of the optic nerve was measured.
p	The anterior cranial base was drilled from the tip of the SOF toward the medial right side, and the distance to the medial margin of the optic nerve was measured.

Table 2

Item	3D synthetic image mean±SD (mm)	RP model mean±SD (mm)	reproducibility of RP model (%)
length			
a	22.41 ± 2.36	22.29 ± 2.49	96/102 (94)
b	18.67 ± 1.58	18.52 ± 1.62	96/102 (94)
c	20.17 ± 1.78	20.02 ± 1.73*	96/102 (94)
d	30.26 ± 3.36	30.20 ± 3.34	96/102 (94)
width			
e	5.31 ± 0.76	5.41 ± 0.77**	97/99 (98)
f	3.77 ± 0.41	3.90 ± 0.45**	98/100 (98)
g	2.99 ± 0.36	3.15 ± 0.39**	98/100 (98)
h	2.41 ± 0.31	2.54 ± 0.31**	90/93 (97)
i	4.26 ± 0.39	4.26 ± 0.47	89/91 (98)
j	2.80 ± 0.42	2.83 ± 0.40	87/90 (97)
k	5.04 ± 0.64	5.14 ± 0.62**	90/99 (91)
l	3.50 ± 0.43	3.60 ± 0.32*	90/99 (91)
length			
m	8.72 ± 1.77	8.75 ± 1.70	94/98 (96)
n	8.42 ± 1.57	8.52 ± 1.60	94/98 (96)
o	8.36 ± 1.50	8.55 ± 1.61*	94/98 (96)
p	10.47 ± 2.12	10.37 ± 2.51	94/98 (96)

Table 3

	the vicinity of the ACP lesion		outside the vicinity of the ACP lesion	
Item	mean ± SD (%)	reproducibility (%)	mean ± SD (%)	reproducibility (%)
a	0.96 ± 3.32	14/16 (88)	-0.34 ± 4.46	82/86 (95)
b	-0.82 ± 3.03	14/16 (88)	-0.91 ± 4.73	82/86 (95)
c	-1.35 ± 3.51	14/16 (88)	-0.72 ± 4.16	82/86 (95)
d	1.02 ± 3.39	14/16 (88)	0.50 ± 4.44	82/86 (95)
e	0.87 ± 4.70	15/15 (100)	3.00 ± 7.88	82/84 (98)
f	3.40 ± 3.73	16/16 (100)	3.66 ± 6.30	82/84 (98)
g	4.07 ± 5.64	16/16 (100)	5.15 ± 7.68	82/84 (98)
h	3.74 ± 7.24	15/15 (100)	5.52 ±10.82	75/78 (96)
i	1.20 ± 4.76	9/9 (100)	1.15 ± 7.64	80/82 (98)
j	6.39 ± 8.21	7/8 (88)	1.84 ± 8.95	80/82 (98)
k	2.48 ± 3.86	10/15 (67)	2.52 ± 5.38	80/84 (95)
l	4.61 ± 5.44	10/15 (67)	3.22 ± 9.70	80/84 (95)
m	-2.63 ± 6.42	14/14 (100)	1.65 ±14.94	80/84 (95)
n	-2.51 ± 6.67	14/14 (100)	2.49 ± 8.99	80/84 (95)
o	1.93 ± 5.65	14/14 (100)	3.34 ±11.76	80/84 (95)
p	-1.04 ± 5.92	14/14 (100)	-0.89 ±11.17	80/84 (95)

Table 4

Identification of the anatomical evaluation items

Item	Score	ICC	95%CI
SOF	3.9±0.32		
OC	3.7 ± 0.48		
ACP	4.0 ± 0.00		
FR	1.9 ± 0.74		
FO	4.0 ± 0.00		
ON	4.0 ± 0.00		
Optic chiasm	4.0 ± 0.00		
IC	4.0 ± 0.00		
M1	4.0 ± 0.00		
A1	4.0 ± 0.00		
		0.98	0.95－0.99

Evaluation items of the intraosseous region after AC

Item	Score	ICC	95%CI
ON	3.9 ± 0.32		
IC	4.0 ± 0.00		
Optic strut	2.6 ± 1.07		
		0.93	0.71－1.00

Comprehensive evaluation

Item	Score
Similarity to the human bone	3.2 ± 0.63
Drilling evaluation	3.7 ± 0.48