CT-based morphometric analysis of the occipital condyle: focus on occipital condyle screw insertion

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OBJECTIVE The segmental occipital condyle screw (OCS) is an alternative fixation technique in occipitocervical fusion. A thorough morphological study of the occipital condyle (OC) is critical for OCS placement. The authors set out to introduce a more precise CT-based method for morphometric analysis of the OC as it pertains to the placement of the segmental OCS, and they describe a novel preoperative simulation method for screw placement. Two new clinically relevant parameters, the height available for the OCS and the warning depth, are proposed.

METHODS CT data sets from 27 fresh-frozen human cadaveric occipitocervical spines were used. All measurements were performed using a commercially available 3D reconstruction software package. The length, width, and sagittal angle of the condyle were measured in the axial plane at the base of the OC. The height of the OC and the height available for the segmental OCS were measured in the reconstructed oblique sagittal plane, fitting the ideal trajectory of the OCS recommended in the literature. The placement of a 3.5-mm-diameter screw that had the longest length of bicortical purchase was simulated into the OC in the oblique sagittal plane, with the screw path not being blocked by the occiput and not violating the hypoglossal canal cranially or the atlantooccipital joint caudally. The length of the simulated screw was recorded. The warning depth was measured as the shortest distance from the entry point of the screw to the posterior border of the hypoglossal canal.

RESULTS The mean length and width of the OC were found to be larger in males: 22.2 ± 1.7 mm and 12.1 ± 1.0 mm, respectively, overall ($p < 0.0001$ for both). The mean sagittal angle was $28.0^\circ \pm 4.9^\circ$. The height available for the OCS was significantly less than the height of the OC (6.2 ± 1.3 mm vs 9.4 ± 1.5 mm, $p < 0.0001$). The mean screw length (19.3 ± 1.9 mm) also presented significant sex-related differences: male greater than female ($p = 0.0002$). The mean warning depth was 7.5 ± 1.7 mm. In 7.4% of the samples, although the height of the OC was viable, the height available for the OCS was less than 4.5 mm, thus making screw placement impractical. For these cases, a new preoperative simulation method of the OCS placement was proposed. In 92.6% of the samples that could accommodate a 3.5-mm-diameter screw, 24.0% showed that the entry point of the simulated screw was covered by a small part of the C-1 posterosuperior joint rim.

CONCLUSIONS The placement of the segmental OCS is feasible in most cases, but a thorough preoperative radiological analysis is essential and cannot be understated. The height available for the OCS is a more clinically relevant and precise parameter than the height of the OC to enable proper screw placement. The warning depth may be helpful for the placement of the OCS.

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KEY WORDS occipital condyle screw; occipitocervical fusion; hypoglossal canal; CT-based analyses; screw trajectory; technique

ABBREVIATIONS OC = occipital condyle; OCJ = occipitocervical junction; OCS = occipital condyle screw.

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AMONG the many possible causes for occipitocervical junction (OCJ) pathology and instability, one can list congenital malformation, degeneration, trauma, and rheumatological diseases that may lead to a variety of consequences such as deformity, pain, cranial nerve dysfunction, progressive myelopathy, paralysis, respiratory dysfunction, or even sudden death.^{4,10,18} OCJ fusion is indicated for cases of craniocervical instability, and the use of rigid internal fixation is well characterized.⁷ The current benchmark procedure constitutes performing a rigid posterior internal fixation employing modular screw-rod instrumentation with a midline occipital keel plate.^{23,28,30} Nevertheless, in cases of suboccipital craniectomy, the suboccipital bone is not available for screw insertion, making occipital keel plate fixation nonviable.^{3,6,20} Additionally, the placement of the occipital screws has been implicated in intracranial injuries as well as epidural hematomas.^{9,22}

Recently, the occipital condyle (OC) became an alternative structure that could be used to address these problems and develop additional anchor points. A promising technique is segmental occipital condyle screw (OCS) fixation.^{1,3,5,6,8,11–17,21,24–27} A few anatomical,^{5,6,12,14–17,21,26} biomechanical,^{8,24,27} and clinical^{11,3,6,11,13,25} studies have identified the feasibility of OCS placement for OCJ fixation. Advantages of the OCS include a decreased length of the lever arm, longer screw length, a low profile that leaves more available bony surface area for grafting, and avoidance of dramatic rod contouring. However, since the OC is very close to vital neurovascular structures, a thorough morphological study of the OC and a surgical plan of the placement of the OCS are critical and need further study.

The objective of this study was to introduce a more accurate method for morphometric analysis of the OC as it pertains to the placement of the OCS. The height available for the OCS, a novel parameter more sensitive to the safety

of the screw placement, is proposed and investigated. We also introduce a novel preoperative simulation method of the OCS placement. A new parameter, termed here the warning depth, is also introduced as the distance from the entry point to the hypoglossal canal.

Methods

CT data sets from 27 fresh frozen human cadaveric occipitocervical spines were used. The donor sample consisted of 16 men and 11 women with an average age of 56.2 ± 8.2 years (range 36–68 years). CT images (Volume Zoom, Siemens Medical Solutions USA) were acquired in the axial plane from the occiput to C-7 in 1.0-mm contiguous slices (120 kV, 100 mA, 1.0-second duration, 20-cm field of view, 512×512 matrix). The occiput–C1 segment was the level of interest. None of the cadavers presented with anatomical abnormalities or pathological changes such as fractures, severe deformity, or metastatic disease as shown on the CT scan. Axial, sagittal, and coronal reconstructions and all measurements were obtained by the first author (J.Z.) using a commercially available segmentation suite (Mimics Research 17.0, Materialise).

Morphological Parameters

The length, width, and sagittal angle of the condyle were measured in the axial plane at the base of the condyle (Fig. 1). The length was measured as the long axis from the anterior edge to the posterior edge. The transverse width was measured as the widest distance. The condylar sagittal angle was measured between the long axis of the condyle and the sagittal midline.

The height of the OC and the height available for the OCS were measured on the reconstructed oblique sagittal plane, fitting the ideal trajectory of the OCS described and recommended in the literature.^{1,14,26} The oblique sagittal plane passed the entry point of the OCS, which was 5.0

FIG. 1. Measurement of the length, width, and sagittal angle of the OC on the axial plane at the base of the OC. Yellow dots indicate the anterior edges of the OC; white dots, the posterior edges of the OC; blue dots, the transversely widest points of the OC; green lines, the OC length; red lines, the OC width; white lines, the long axis of the OC (parallel to the line formed by the yellow and white dots); orange lines, the sagittal midlines.

FIG. 2. Reconstruction of oblique sagittal planes fitting the ideal trajectory of the OCS. *Black planes* indicate the oblique sagittal planes passing the entry point of the screw 5 mm lateral (*red line*) to the posteromedial edge of the OC (*arrow*). The hypoglossal canals are shaded in *green*.

mm lateral to the posteromedial edge of the condyle. It also was parallel to the sagittal angle of the OC, ensuring that the longest screw length possible could be achieved (Fig. 2).

On this oblique sagittal plane, a vertical line was drawn connecting the bottom of the hypoglossal canal and the condylar bony articular surface. This linear segment was defined as the height of the OC. An atlantooccipital joint line was drawn passing the highest points of the anterior and posterior edges of the atlantooccipital joint. The intersection between the aforementioned vertical line and the atlantooccipital line was determined, and the distance between the intersection and the bottom of the hypoglossal canal was defined as the height available for the OCS (Fig. 3).

FIG. 3. Measurement of the height of the OC and the height available for the OCS on the reconstructed oblique sagittal plane. The *yellow dots* indicate the bottom of the hypoglossal canal (1), the intersection between a vertical line drawn from Dot 1 and condylar articular surface (2), anterior edge of the atlantooccipital joint (3), posterior edge of the atlantooccipital joint (4), and the intersection between Line 1–2 and Line 3–4 (5). H1 indicates the height available for the occipital condyle screw (length of Line 1–2); and H2, the height of the occipital condyle (length of Line 1–5).

FIG. 4. Simulation of the screw placement. **Upper:** Bottom view. **Lower:** Posteroanterior view. The hypoglossal canals and screws are highlighted in *green* and *red*, respectively.

Screw Placement Simulation

The placement of a 3.5-mm-diameter screw into the OC was simulated on the oblique sagittal plane (Figs. 4 and 5). The ideal screw placement had the longest length of bicortical purchase and did not violate the hypoglossal canal cranially or the atlantooccipital joint caudally. Also, the entry point of the screw should not be obstructed by the posterosuperior rim of C-1 (Fig. 6). Hence, a line was drawn through the bottom of the posterior occiput and the hypoglossal canal. Then a 3.5-mm-diameter cylinder

FIG. 5. Simulation of screw placement and measurement of the warning depth. The *yellow box* indicates the projection of a cylinder 3.5 mm in diameter stimulating the OCS; the *white line*, the upper border connecting the bottom of the posterior occiput and the bottom of the hypoglossal canal. The warning depth is measured as the shortest distance from the entry point of OCS to the posterior border of the hypoglossal canal (*red line*).

FIG. 6. Entry point of the OCS obstructed by the posterosuperior rim of C-1. An osteophyte is also present. The *yellow box* indicates the projection of a cylinder 3.5 mm in diameter simulating the OCS; the *red line*, the upper border connecting the bottom of the posterior occiput and the bottom of the hypoglossal canal; and the *yellow arrow*, the entry point of the OCS.

simulating the screw was placed parallel and 1.0 mm inferior to this line. The 1.0-mm gap served as the error space of the placement. The simulation was reviewed on several continuous axial, sagittal, and coronal images to make sure no violation of the hypoglossal canal and the atlanto-occipital joint occurred. The length of the simulated screw was recorded. The shortest distance from the entry point of the OCS to the posterior border of the hypoglossal canal was also measured and termed the “warning depth” to avoid penetration of the OCS into the hypoglossal canal in case the OCS was placed in the wrong orientation (Fig. 5).

Statistical Analysis

All measurements were collected and analyzed using Statview (version 5.0, SAS Institute). The mean $\pm$ SD and the 95% confidence interval were calculated for all parameters. Sex differences were assessed using a 2-sample *t*-test with equal variances. A paired Student *t*-test was used to compare the differences between the right and the left sides and the differences between the height of the OC and the height available for the OCS. The level of significance was set at $p < 0.05$ for all statistical analyses.

Interobserver and Intraobserver Variability

To provide validity to the measurements and the method used to obtain them, one coauthor (X.K.) contributed to this study by being a second observer in addition to the first author, who, as mentioned before, was the main observer for all measurements. Both investigators took measurements of all the parameters mentioned in this study twice in the span of 2 weeks. Additionally, the parameters were measured for both sides of the occipital condyle (left and right), rendering a set of 560 individual measurements per observer. These are detailed as follows: 7 parameters (length, width, sagittal angle, height of the OC, height available for the OCS, screw length, and finally the warning depth) for both sides, measured 2 times per investigator (2 investigators), for 10 specimens yields the above-mentioned 560 observations. With this data set, the inter- and intraclass correlation coefficients were calculated using SPSS Statistics (version 23, IBM).

Results

The results obtained from the linear and angular measurements are presented in Table 1. The height available for the OCS was significantly smaller than the height of the OC (6.2 ± 1.3 vs 9.4 ± 1.5 mm, $p < 0.0001$). In 2 samples (4 sides), although the height of the OC was greater than 4.5 mm (i.e., a 3.5-mm-diameter screw plus 1.0-mm error space), the height available for the OCS was less than 4.5 mm and it was not feasible to accommodate the OCS. Both the length and the width of the OC in males were significantly greater than in females ($p < 0.0001$).

The results of the analysis of the simulated OCS placement are presented in Table 2. The 2 samples mentioned above were excluded. The possible screw length in males was significantly larger than in females ($p < 0.0001$). The shortest distance from the entry point of OCS to the posterior border of the hypoglossal canal did not show significant differences between both sides, confirming structural symmetry.

Among a total of 25 samples that could accommodate a 3.5-mm-diameter screw, 6 samples (12 sides) showed that the entry point of the simulated screw was covered by a small part of the C-1 posterosuperior joint rim and/or osteophytes (Fig. 6).

Variability

The inter- and intraclass correlation coefficients obtained for both investigators when measuring the parameters reported in this study showed very good to excellent correlation both in terms of inter- and intraobserver repeatability. The lowest coefficient was 0.910 and the highest 0.998. All results are shown in Table 3.

Discussion

The use of rigid internal fixation is critical for a successful OCJ fusion. The procedure has undergone significant evolution from simple autograft onlay fusion to sublamina wiring and, most recently, the modular midline occipital keel plate connected via rods to atlantoaxial or subaxial screw fixation.^{23,28,30} Unlike the cervical end of the OCJ, for which many rigid fixation techniques exist, such as the lateral mass screw, C-2 translamina screw, and C1–2 transarticular screw, most limitations for the use of OCJ fixation systems come from the cranial end.^{22,23}

An important source for possible issues with the OCS technique is the complex geometry of the cranial base. Although this novel technique shows promise, challenging local anatomy with vital surrounding structures cannot be understated. The OC is bordered rostrally by the hypoglossal canal, caudally by the occiput–C1 joint, medially by the foramen magnum, and laterally by the jugular bulb and carotid artery.^{5,6,12,14–17,21,26} In the rostrocaudal direction, if the OCS is placed too rostrally, it may violate the hypoglossal canal and cause injury to the hypoglossal nerve; if it is placed too caudally, it may violate the occiput–C1 joint, which some authors think might weaken the fixation.¹⁶

Earlier studies attempted to characterize the OC's dimensions either with cadaveric specimens^{5,6,12,21,26} or via CT data of clinical patients^{6,14–17} to assess OCS placement

TABLE 1. CT analysis of OC anatomy*

Variable	No. of Samples (sides)	Length (mm)			Width (mm)			Sagittal Angle (°)			OC Height (mm)			Height Available for OCS (mm)		
		Mean ± SD	95% CI		Mean ± SD	95% CI		Mean ± SD	95% CI		Mean ± SD	95% CI		Mean ± SD	95% CI	
Sex																
Male	16 (32)	23.16 ± 1.37	22.68–23.63		12.54 ± 0.98	12.20–12.87		27.34 ± 4.99	25.61–29.07		9.63 ± 1.30	9.18–10.08		6.29 ± 1.29	5.84–6.74	
Female	11 (22)	20.85 ± 1.06	20.40–21.29		11.51 ± 0.79	11.18–11.85		29.05 ± 4.60	27.13–30.97		9.03 ± 1.73	8.31–9.76		6.17 ± 1.30	5.63–6.71	
p value		<0.0001			<0.0001			0.207			0.156			0.746		
Side																
Right	(27)	22.37 ± 1.75	21.71–23.03		12.08 ± 0.92	11.73–12.43		28.55 ± 4.69	26.78–30.32		9.40 ± 1.63	8.79–10.01		6.32 ± 1.34	5.82–6.83	
Left	(27)	22.06 ± 1.64	21.44–22.68		12.16 ± 1.15	11.73–12.59		27.53 ± 5.07	25.62–29.44		9.37 ± 1.40	8.84–9.90		6.16 ± 1.24	5.69–6.63	
p value		0.086†			0.660			0.186			0.881			0.515		
Total	27 (54)	22.22 ± 1.69	21.76–22.67		12.12 ± 1.03	11.84–12.39		28.04 ± 4.86	26.74–29.34		9.39 ± 1.50†	8.98–9.79		6.24 ± 1.28	5.90–6.58	

* Boldface type indicates statistical significance.

† Statistical trend.

‡ p < 0.0001 compared with height available for the OCS.

feasibility. Most of these studies took the height of the OC as the height available for the OCS.^{5,6,12,14,16,21,26} However, it is known that the articular surface of the OC is curved and convex inferiorly. Therefore, the actual height available for the segmental OCS should subtract the height of the articular surface from the height of the OC to prevent the OCS from being placed into the articular surface. Another criticism of these previous studies^{5,6,14,17,19} is that the measurement method of the height of the OC is inconsistent and of questionable precision. In some cases, researchers have measured the distance from the lower margin of the hypoglossal canal's internal opening and the lower margin of the occipital condyle;^{5,19} while others have measured this distance on the sagittal and/or coronal CT slice perpendicularly from the hypoglossal canal to the condylar cartilage.^{6,14,17} Due to the inclined articular surface of the OC, the height is different at different locations. The choice of the CT slice on which to make the measurement also seems to be somewhat arbitrary.

For the first time, we have distinguished the height available for the OCS from the height of the OC and also measured the height of the OC in a more clinically relevant way: on the oblique parasagittal plane fitting the ideal trajectory of the OCS. The height available for the OCS is 6.2 ± 1.3 mm, which is significantly shorter than the height of the OC: 9.4 ± 1.5 mm. In 7.4% of cases, although it was feasible to accommodate a 3.5-mm-diameter screw within the OC height, the available height for the OCS screw was less than 4.5 mm (a 3.5-mm-diameter screw plus 1 mm error space) and it did not permit correct placement of the OCS. The height available for the OCS is a more accurate parameter to assess the feasibility of the placement of the segmental OCS. Other parameters, such as the length, width, and sagittal angle, were measured on the axial plane at the base of the OC, and the results were consistent with the results of previous studies.^{5,6,12,14,16,21,26}

Simulated OCS Placement

A 3D CT-based simulation method for OCS placement was also developed. First, an oblique sagittal plane fitting the ideal trajectory of the OCS was created. The best-fitting oblique sagittal plane passed through the entry point of the OCS and followed the sagittal angle of the OC to obtain a longer screw length. Several OCS entry points have been proposed in the literature; Uribe et al. described the location as being 4–5 mm lateral to the posteromedial edge of the foramen magnum at its junction with the OC and the condylar fossa.^{1,14,26} La Marca et al. described it as 3 mm inferior to the condylar emissary vein foramen along the midline of the condyle itself.¹² Frankel et al. suggested the entry point of the OCS to be lateral to the condylar canal at the lateral edge of the condylar fossa just below the skull base.⁶ We followed Uribe's method, and the entry point of the OCS chosen in the study was 5 mm lateral to the posteromedial edge of the condyle. An advantage for using Uribe's method is less potential to violate the emissary vein located in the posterior condylar foramen, which is the lateral border of the entry point.²⁶

Second, taking all the anatomy restrictions into consideration, the placement of the OCS with the best possible trajectory was simulated. In the rostrocaudal direction,

TABLE 2. CT analysis of the simulated OCS placement*

Variable	No. of Samples (sides)	Screw Length (mm)		Warning Depth (mm)	
		Mean $\pm$ SD	95% CI	Mean $\pm$ SD	95% CI
Sex					
Male	15 (30)	20.04 $\pm$ 1.70	19.43–20.65	7.58 $\pm$ 1.70	6.98–8.19
Female	10 (20)	18.18 $\pm$ 1.48	17.53–18.83	7.44 $\pm$ 1.73	6.68–8.20
p value		<0.0001		0.775	
Side					
Right	(25)	19.30 $\pm$ 1.82	18.59–20.02	7.89 $\pm$ 1.68	7.23–8.54
Left	(25)	19.28 $\pm$ 1.91	18.53–20.03	7.17 $\pm$ 1.67	6.51–7.82
p value		0.935		0.010	
Total	25 (50)	19.29 $\pm$ 1.85	18.78–19.81	7.53 $\pm$ 1.70	7.06–8.00

* Boldface type indicates statistical significance.

the bottom of the occiput and the hypoglossal canal make up the rostral limit of the placement of the OCS,¹⁶ while the horizontal segment of the vertebral artery and the occiput–C1 joint the caudal limit. Taking these into consideration, the screw placement was simulated by placing it parallel to and 1.0 mm inferior to the upper border line, which was the line connecting the bottom of the occiput and the hypoglossal canal. The 1.0-mm interval served as the error space of the placement. The simulated screw was placed higher in the OC as to gain as much bicortical purchase as possible because the shape of the OC is convex inferiorly. Meanwhile, placing the screw higher keeps it far away from the vertebral artery, thus lowering the chance of vessel injury, a most dangerous complication.

An interesting finding in the study is that the entry point of the simulated screw may be covered by the C-1 posterosuperior joint rim (6 samples/12 sides of the 25 samples/50 sides attempted). One possible explanation for this can be attributed to settlement of the OC due to the degenerative change of the atlantooccipital joint, which might correlate to the old age of the specimens used in this study. There are several different descriptions about the craniocaudal posi-

tion of the entry point in the literature.^{1,6,16,26} As the entire range available in the craniocaudal direction is very limited, actually none of these descriptions had a significant difference. The recommended position is 1–2 mm rostral to the atlantooccipital joint and at least 2 mm caudal to the skull, with the intention of making enough room to accommodate the 3.5-mm-diameter screw.^{1,14,15,25,26} Based on our new findings, the ideal entry point is not always rostral to the atlantooccipital joint. In some cases it would be a millimeter caudal to the atlantooccipital joint. Then a small part of the C-1 posterosuperior joint rim should be removed to get the optimal entry point of the OCS in the craniocaudal direction. In theory, the entry point in the craniocaudal direction could also be blocked from the hyperextension of the atlanto-occipital joint. Therefore, the extension-flexion status of the atlantooccipital joint should be cautiously evaluated during the surgery.

Warning Depth

A new parameter, named the warning depth was proposed as the shortest distance from the entry point of the screw to the posterior border of the hypoglossal canal. It

TABLE 3. Interobserver and intraobserver correlation coefficients

Comparisons	Length	Width	Sagittal Angle	OC Height	Height Available for OCS	Screw Length	Warning Depth
Interobserver							
Investigator 1 Right 1st vs 2nd	0.922	0.910	0.979	0.997	0.963	0.993	0.991
Investigator 1 Left 1st vs 2nd	0.930	0.979	0.967	0.953	0.982	0.993	0.998
Investigator 2 Right 1st vs 2nd	0.955	0.971	0.990	0.994	0.994	0.993	0.990
Investigator 2 Left 1st vs 2nd	0.972	0.991	0.993	0.994	0.990	0.993	0.998
Minimum	0.922	0.910	0.967	0.953	0.963	0.993	0.990
Maximum	0.972	0.991	0.993	0.997	0.994	0.993	0.998
Intraobserver							
Investigator 1 Right 1st vs 2nd	0.963	0.950	0.975	0.994	0.986	0.994	0.995
Investigator 1 Left 1st vs 2nd	0.951	0.978	0.972	0.966	0.989	0.993	0.998
Investigator 2 Right 1st vs 2nd	0.956	0.947	0.982	0.993	0.993	0.991	0.996
Investigator 2 Left 1st vs 2nd	0.981	0.974	0.994	0.989	0.987	0.996	0.998
Minimum	0.951	0.947	0.972	0.966	0.986	0.991	0.995
Maximum	0.981	0.978	0.994	0.994	0.993	0.996	0.998

is proposed as a valuable parameter to keep the surgeon aware of any possible breach of the hypoglossal canal during surgery. During the drilling procedure, if great resistance is encountered, effectively halting forward motion, the warning depth will indicate contact with the hypoglossal canal and the surgeon should adjust the trajectory accordingly. The distance between the posterior border of the OC and intracranial terminal of the hypoglossal canal has been studied in the transcondylar approach,^{2,29} but the warning depth is measured on the trajectory of the OCS and more specifically dedicated to the placement of the OCS.

We acknowledge some limitations in this study: the sample size and old age of the subjects might not be ideal for a normative study. However, it must also be mentioned that the focus of this report is to develop the analysis technique and not to provide normative reference values, and to further clarify some concepts and propose a preoperative planning method. Also, there are some other possible trajectories for the OCS that might be applicable depending on the particular case being analyzed. Here, we only simulate the optimal trajectory of the OCS recommended in the literature to obtain the longest possible bicortical purchase, which is the best clinical scenario. However, the new parameters and the simulating method apply the same to other trajectories. This study was conducted on nonpathological specimens; however, several other pathologies might change the OC anatomy, thus presenting additional complications to the surgeon preparing the case.

Conclusions

The height available for the OCS is a more clinically relevant and accurate parameter than the height of the OC to assess the feasibility of screw placement. A method of preoperative simulation of the OCS placement based on the CT data was introduced together with a new parameter, the warning depth. The placement of the OCS is feasible in most cases, but a thorough preoperative radiological morphological study of the OC and a surgical plan of the placement of the OCS are critical and cannot be understated.

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Disclosures

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Author Contributions

Conception and design: Inoue, Zhou, Espinoza Orías, Kang, Zhang. Acquisition of data: Zhou, Espinoza Orías, Kang, He. Analysis and interpretation of data: Inoue, Zhou, Espinoza Orías, Kang, He. Drafting the article: Zhou, Espinoza Orías. Critically revising the article: Inoue, Zhou, Espinoza Orías, Zhang, An. Reviewed submitted version of manuscript: all authors. Statistical analysis: Espinoza Orías. Administrative/technical/material support: Inoue, Kang, Zhang, An. Study supervision: Inoue, Espinoza Orías, An.

Supplemental Information

Previous Presentations

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