



Original Article

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A Universal Craniometric Index for Establishing the Diagnosis of Basilar Invagination

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Objective: The conventional criteria for defining the basilar invagination (BI) focus on the relationship of odontoid tip to basion and opisthion, landmarks that are intrinsically variable especially in presence of occipitalised atlas. A universal single reference line is proposed that helps in unequivocally establishing the diagnosis of BI, may be relevant in establishing both Goel types A and B BI, as well as in differentiating a 'very high' from 'regular' BI.

Methods: Study design – case-control study. In 268 patients (group I with BI [n = 89] including Goel type A BI [n = 66], Goel type B BI [n = 23], and group II controls [n = 179]), the perpendicular distance between odontoid tip and line subtended between posterior tip of hard palate-internal occipital protuberance (P-IOP line) was measured. Logistic regression analysis determined factors influencing the proposed parameter ($p < 0.05$).

Results: In patients with a 'very high' BI (n = 5), the odontoid tip intersected/or was above the P-IOP line. In patients with a 'regular' BI (n = 84), the odontoid tip was 6.56 ± 3.9 mm below the P-IOP line; while in controls, this distance was 12.53 ± 4.28 mm ($p < 0.01$). In Goel type A BI, the distance was 7.01 ± 3.78 mm and in type B BI, it was 5.07 ± 4.19 mm ($p = 0.004$). Receiver-operating characteristic curve analysis identified 9.0 mm (8.92–9.15 mm) as the cut-point for diagnosing BI using the odontoid tip-P-IOP line distance as reference.

Conclusion: The odontoid tip either intersecting the P-IOP line (very high BI) or being < 9 mm below the P-IOP line (Goel types A and B BI) is recommended as highly applicable criteria to establish the diagnosis of BI. This parameter may be useful in establishing the diagnosis in all varieties of BI.

Keywords: Basilar invagination, Craniovertebral junction, Craniometric line, Odontoid, Diagnosis, Chamberlain line



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INTRODUCTION

Basilar invagination (BI) is the "invagination of the upper vertebral column into the skull base."¹ Its diagnosis was based on craniometric lines that were demarcated on conventional plain radiology and tomograms.²⁻⁴ The multiplanar magnetic resonance imaging (MRI) and spiral 3-dimensional (3D) computed tomography (CT) scan images in the present era requires

a universally applicable parameter to assess the presence of BI. There are several reasons for proposing a new and universally relevant radiological parameter for the evaluation of BI.

Congenital atlantal occipitalisation (OA), a common craniovertebral junction (CVJ) anomaly, has a prevalence rate between 0.08%–2.8% in the general population⁵⁻⁷ and is associated with BI in 70%–80% of cases.⁸⁻¹⁰ In the presence of OA, it is often not possible to accurately delineate the basion and/or opisthion be-

cause it is fused with both the clivus and the occiput, respectively. Clival segmentation anomalies or occipital bone hypoplasia result in variability in accurately locating the basion and opisthion, leading to problems in accurately subtending the McRae, Chamberlain, and McGregor lines on both lateral plain radiographs and on CT and MRI scans (Fig. 1A, B). Moreover, any lateral tilt or torticollis will change the sagittal plane in which the opisthion is being evaluated. The resultant interobserver variation, therefore, often results in an inaccurate assessment of

BI on both dynamic flexion and extension imaging and in the comparison of the preoperative and postoperative imaging after a surgical procedure like posterior distraction and fusion has been performed.^{11,12} Different authors have used different cutoff values for establishing the diagnosis of BI; the height of the odontoid has been variably established to be 2 mm, 5 mm, or 6.6 mm above the Chamberlain line, for the condition to be diagnosed as BI. This directly affects the incidence of BI quoted in the literature in various studies.^{11,13}

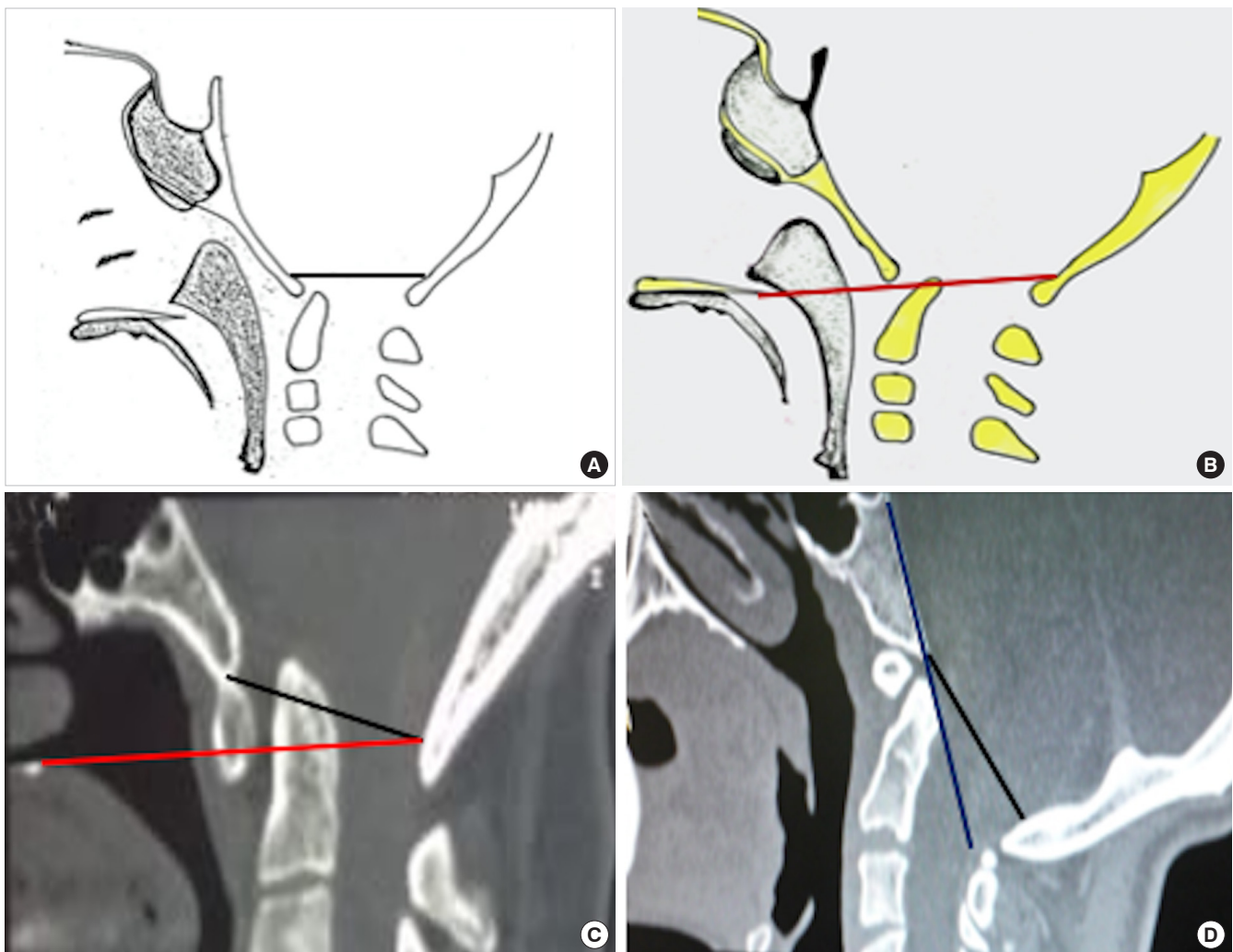


Fig. 1. Schematic diagram showing the 2 important craniometric lines utilized for diagnosing BI: (A) the McRae line subtended from the basion to the opisthion and (B) the Chamberlain line subtended from the posterior tip of the hard palate to the opisthion. As both patients have an occipitalized atlas, the actual position of the opisthion and basion, and therefore, the actual measurement of the position of the tip of the odontoid relative to this line, are difficult to precisely determine. Midsagittal reconstructed images of computed tomography scan showing (C) Goel type A BI (with the central invagination of the odontoid into the foramen magnum) with the odontoid tip being above the McRae line and > 2 mm above the Chamberlain line. (D) In Goel type B BI (with clival hypoplasia and occipital condylar hypoplasia, with or without platybasia, with a significant cervicomedullary compression due to the posteriorly directed tip of the odontoid), the tip of the odontoid remains below the McRae line and the Wackenheim clivus line. Thus, the latter 2 craniometric indices cannot be used as effective craniometric indices to diagnose BI.

According to the Goel classification, BI can be of 2 types (Fig. 1C, D).¹¹ In Goel type A BI, atlantoaxial dislocation is associated with the upper portion of odontoid process ‘invaginating’ into the foramen magnum, and therefore, being located above the Chamberlain, McRae, and Wackenheim clival lines. In Goel type B BI, the odontoid process and clivus remain anatomically aligned to each other, with the neurological deficits being mainly due to a significant posterior arching of a highly placed odontoid, due to an associated occipital condylar hypoplasia. In this type of BI, the tip of the odontoid process remains above Chamberlain line but below the McRae and Wackenheim lines. This, in effect, means that Goel type B BI cannot be evaluated using McRae line or Wackenheim line. An ideal reference line should be able to address both the types of BI.

In this study, simple bony landmarks that are easily identifiable and consistently reproducible in establishing the presence of BI on midsagittal MRI and CT images are being proposed. These landmarks are neither affected by the concomitant presence of OA, clival anomalies nor by the presence of the type of BI in a patient.

MATERIALS AND METHODS

The article is written according to the STROBE (STrengthening the Reporting of Observational Studies in Epidemiology)

statement guidelines. The ethical committee permission of the institute has been taken for conduction of the study (IEC code No. 2013-08-MCH-67). As per our departmental policy, an informed consent is taken from all patients regarding the permission to include radiological details for research and publication.

1. Study Design

Case-control observational study

2. Participants

In this cross-sectional observational study, radiological imaging of 351 patients (age > 16 years), operated between June 2012 and March 2019, were analysed (Fig. 2). Sixty-three of them with either os odontoideum, inflammatory, tuberculous, or traumatic atlantoaxial dislocation and 20 of them, where the desired osseous landmarks were not visible on radiological imaging, were excluded. Thus, 268 patients (group I, consisting of 89 patients in whom BI was visible on either sagittal CT reconstruction [n=25] or sagittal MRI [n=64]); and group II with 179 control patients (with CT image [n=48] or MRI [n=131]), having either a lower cervical or lumbar degenerative disease, in whom a screening cervical spine CT or MRI scan had also been performed) were recruited for the final analysis. Demographic details, clinical profiles, and radiological data were assessed in all the patients of groups I and II. The radiological imaging of

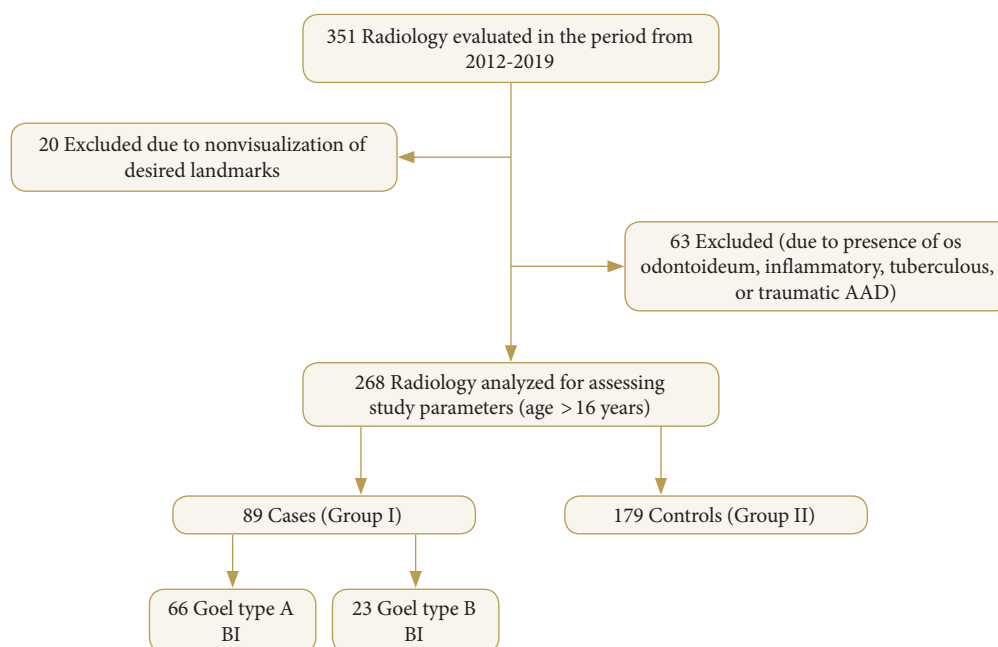


Fig. 2. Flow diagram showing the selection of patients in our study and the inclusion criteria. AAD, Atlantoaxial dislocation; BI, basilar invagination.

each of these patients in the study was evaluated by 2 independent sets of observers (2 radiologists and 2 neurosurgeons) and recorded. During the final analysis, the mean value of measurements with standard deviation was selected.

3. MRI and CT Imaging Protocol

The conventional cervical spine MRI with an extended field of view (FOV) included the posterior end of hard palate (including the internal occipital protuberance) as the upper limit, and the lower end of C7 vertebra as the lower limit. It was done on a 3Tesla-MR scanner (Signa Hdxt, General Electric Medical System, Waukesha, MI, USA) with standard 16-channel high-level-synthesis spine coil. These patients underwent sagittal T2, sagittal T2 fat-saturated, sagittal T1, and axial T2 sequences using bandwidth 41.6, phase 256, FOV 26 cm, slice thickness 3 mm, interslice gap of 0.3 mm, and number of excitations of 4.

A 64-slice multidetector CT scan (Brilliance 190P 64-channel CT scanner, PHILIPS, Amsterdam, The Netherlands) or a 128-slice multiple detector computed tomography (SOMATOM Definition AS+ 64544, SIEMENS, Munich, Germany) was performed. The unenhanced CT scan was performed with the FOV extending from the vertex to the C6 vertebra. The detector configuration was 64 mm × 3 mm/128 mm × 0.6 mm, section thickness 3 mm, section increment 1.5 mm, kilovoltage peak 120 kVp, tube current-time product 200 mAs with image reconstruction upto 1 mm. The images were reconstructed in true axial, coronal, and sagittal planes.

4. Craniometric Analysis of BI

In group I patients, BI was diagnosed using McRae line (odontoid tip being above the line joining anterior margin [basion] and posterior margin of foramen magnum [opisthion]) and/or

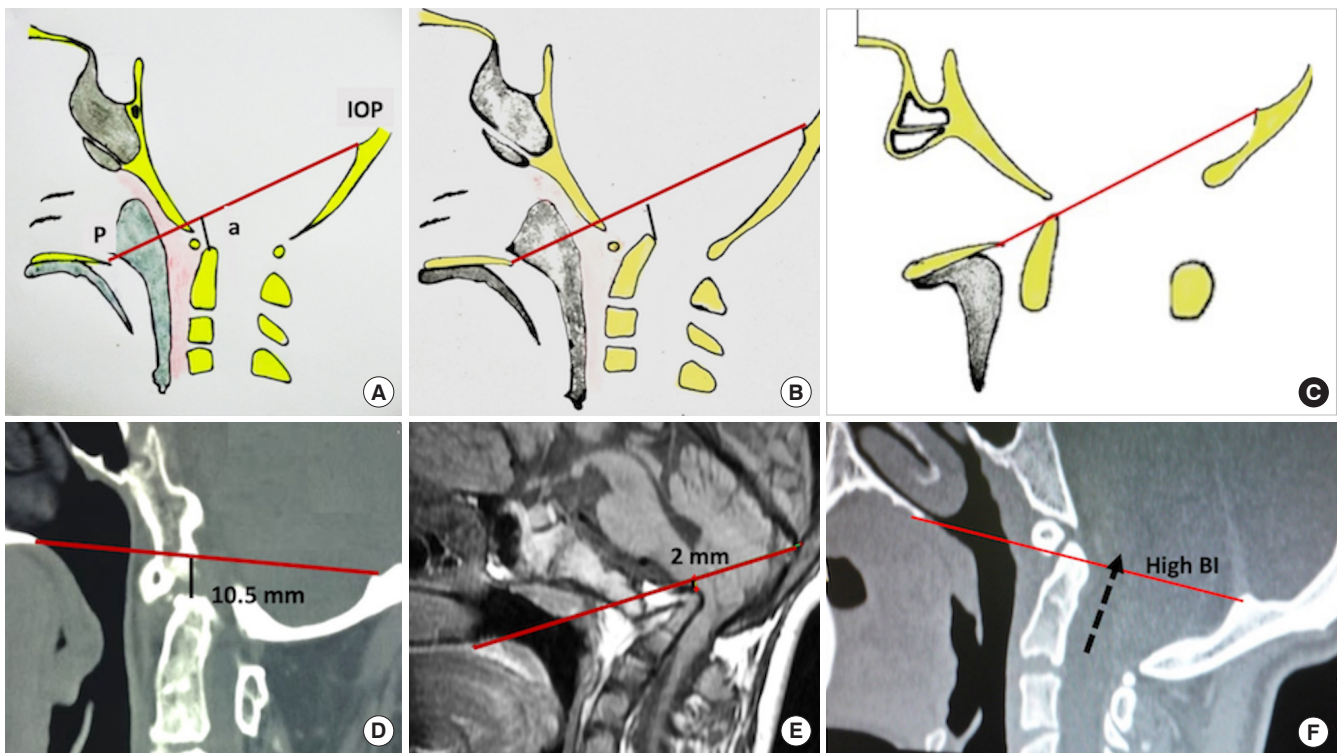


Fig. 3. (A-C) The P-IOP line connects the tip of posterior-most part of the hard palate (P) to the internal occipital protuberance (IOP). The minimum perpendicular distance (a) between the tip of the odontoid process and the P-IOP line is measured on mid-sagittal reconstructed computed tomography (D) and mid-sagittal cervical magnetic resonance imaging (E) image to establish the diagnosis of basilar invagination (BI). While utilizing the criterion of the perpendicular distance between the P-IOP line and the tip of odontoid, the 2 landmarks are clearly definable even in the presence of an occipitalised atlas as well as torticollis. Thus, there is no BI seen in panel D, where the perpendicular distance between the odontoid tip to the P-IOP line is 10.5 mm. Panels E and F demonstrate the 2 categories of patients with BI identified using the criteria of the odontoid tip and the P-IOP line. Those with a regular BI, where the tip of odontoid remained ≤ 9.0 mm below the P-IOP line (E); and, those with a very high BI, where the tip of odontoid was at or above the P-IOP line (F).

Chamberlain line (odontoid tip being >2 mm above the line joining posterior tip of hard palate to opisthion).^{3,4} Further, Goel type A BI (atlantoaxial instability associated with odontoid tip invaginating into foramen magnum above McRae line) (Fig. 1C), and Goel type B BI (no atlantoaxial instability, or clival or atlantoaxial malalignment is seen; clival hypoplasia with or without platybasia and occipital condylar hypoplasia is seen; odontoid tip remains below the foramen magnum but the odontoid and C2 body curves posteriorly causing significant cervicomedullary compression) were classified (Fig. 1D).¹¹

5. Proposed Reference Line for BI

A line connecting the posterior tip of hard plate (P) to the internal occipital protuberance (IOP) is drawn (P-IOP line). The minimum perpendicular distance between the P-IOP line and the odontoid tip was measured on midsagittal cervical MRI image or midsagittal reconstructed CT scan image (Fig. 3A–C). The distance was noted in both group I patients with BI ($n = 89$) and in group II control patients ($n = 179$). The mean distance was compared in both the groups in 268 patients. To evaluate the variability of measurements on different imaging modalities, in the initial 10 patients recruited in the present study, the distance of odontoid tip to P-IOP line was assessed on both midsagittal CT and MRI scans. This evaluation revealed similar values of the distance measuring on both imaging modalities. Two categories of patients were identified using the distance of odontoid tip relative to the P-IOP line: those with regular BI, where the tip of odontoid remained below the P-IOP line (Fig. 3D, E); and those with a very high BI, where the tip of odontoid was above the P-IOP line (Fig. 3F). In 89 patients, we also compared the perpendicular distance from odontoid tip to P-IOP line versus odontoid tip to the well-established Chamberlain line.

6. Clival Length and Suboccipital Length

An assessment of the impact of variability in the length of clivus and the height of IOP from foramen magnum on the establishment of diagnosis of BI was also done. The clival length (CL) was calculated by measuring the distance between dorsum sellae and basion. The occipital length (OL) was calculated by measuring the distance between IOP and opisthion (Fig. 4) These measurements were conducted in the 89 group I patients with BI and in 66 group II control patients. The mean CL and OL were compared between groups I and II patients.

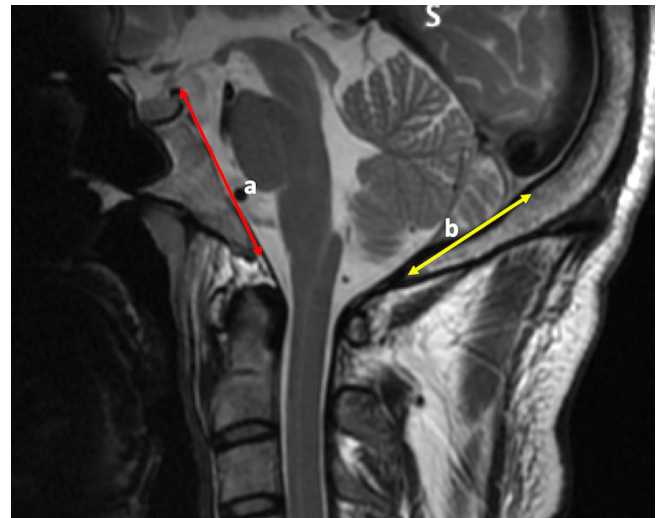


Fig. 4. The clival length (a) is measured by subtending a tangential line from the dorsum sellae to basion; and, the suboccipital length (b) is measured by subtending a line from the internal occipital protuberance to the opisthion.

7. Statistical Analysis

The normality of the continuous variables was assessed and considered normally distributed when the z-score of skewness was within ± 3.29 . Independent samples t-test was used to compare the mean distance from odontoid tip to the P-IOP line between the BI group (including Goel types A and B BI) and the control group as the distance was normally distributed. The area under the receiver-operating characteristic (ROC) curve was used to estimate the diagnostic accuracy and to define the cutoff values with corresponding sensitivity and specificity. Spearman rank correlation (ρ) was used to test the linear relationship between variables. Coefficient of variation (COV) was utilized to check the variability in CL and OL. Binary logistics regression analysis was conducted to determine the predictors affecting the distance between odontoid tip and P-IOP line. A p-value of <0.05 was considered statistically significant. The statistical analyses were performed using IBM SPSS Statistics ver. 23.0 (IBM Co., Armonk, NY, USA).

RESULTS

1. Participants

In the study, 268 patients (male:female = 151:117) were analysed. The distribution of age (group I [with BI]: $n = 89$; mean age, 40.7 ± 15.2 years; range, 17–73 years; group II [control]: $n = 179$; mean age, 45.5 ± 14.8 years; range, 17–81 years) and the sex ratio (group I: male:female = 56:33; group II: male:female =

Table 1. Various craniovertebral junction malformations in group I (with BI) patients (n = 89)

Malformations	No. of patients (%)
Goel type A BI	66 (74.2)
Goel type B BI	23 (25.8)
Occipitalisation of atlas	64 (72.0)
Irreducible AAD*	25 (28.1)
Platybasia [†]	13 (14.6)
Syringomyelia	39 (43.8)
Chiari malformation [‡]	21 (23.6)
Clivus segmentation anomaly	12 (13.5)

BI, basilar invagination; AAD, Atlantoaxial dislocation.

*Irreducible AAD is defined on the basis of failure of reduction in the atlantodental interval on the cervical extension view of the pre-operative dynamic midsagittal computed tomography scan of the craniovertebral junction. [†]Platybasia is characterized by abnormal flattening of the skull base, as defined as a basal angle of more than 140°. [‡]Chiari malformation was diagnosed when the tonsillar herniation was below 5 mm from the foramen magnum.

94:84) were comparable between the 2 groups ($p > 0.05$). In group I, there were 66 patients (74.2%) with Goel type A BI; and 23 patients (25.8%) with Goel type B BI. Out of 89 patients in group I, 64 (72%) had an associated occipitalised atlas (Table 1).

2. Assessment of BI Using P-IOP Line

Two categories of group I (BI) patients were identified using the P-IOP line for diagnosis of BI.

1) Patient with the odontoid tip being above the P-IOP line (n=5)

Five subjects in this category constituted the very high BI group. These 5 patients belonging to group I had the tip of odontoid being higher than the P-IOP line. They were excluded from the analysis. The mean distance of the tip of the odontoid process above the P-IOP line was 6.47 ± 5.1 mm in this category of patients. These included 2 patients with Goel type A BI and 3 patients with Goel type B BI.

2) Patient with the odontoid tip being below the P-IOP line (n=84)

These were assigned to the regular BI group. The mean distance of the tip of the odontoid process from the P-IOP line was 6.56 ± 3.9 mm in the group I (BI) patients in this category. This mean distance was 12.53 ± 4.28 mm in the group II (control) patients. This difference was highly significant ($p < 0.001$).

In patients in whom the odontoid tip was below the P-IOP line, the mean distance of odontoid tip from the P-IOP line in Goel type A BI patients was 7.01 ± 3.78 mm, and in Goel type B

Table 2. Comparison of the mean distance between the tip of odontoid process and the P-IOP line among patients of groups I (with BI) and II (control group)

Group	Distance (mm) from the tip of odontoid to P-IOP		p-value
	Mean \pm SD	Median (range)	
Group I (BI) (n = 84)*	6.56 ± 3.9	6.57 (0–19.5)	$< 0.001^{\S}$
Goel type A BI (n = 64) [†]	7.10 ± 3.78	7.09 (0–19.5)	0.044
Goel type B BI (n = 20) [‡]	5.07 ± 4.19	4.04 (0–13.1)	
Group II (control) (n = 179)	12.53 ± 4.28	12.40 (1.41–24.9)	

P-IOP, posterior tip of the hard palate to the internal occipital protuberance; BI, Basilar invagination; SD, Standard deviation.

The distance was measured from tip of odontoid to the proposed reference line (P-IOP line). There were significant lower values of the mean distance in the group I patients (with BI) when compared to the group II patients (without BI) who served as controls (6.56 ± 3.90 vs. 12.53 ± 4.28 , $p < 0.001$). The mean distance was also significantly different among patients (with BI) who had either Goel type A BI or Goel type B BI (7.10 ± 3.78 vs. 5.07 ± 4.19 , $p = 0.04$). Independent samples t-test used. $p < 0.05$ significant.

*Five patients belonging to group I had the tip of odontoid being higher than the P-IOP line. These patients were classified as the 'very high BI' group. They were excluded from this analysis. The mean distance of the tip of the odontoid process above the P-IOP line was 6.47 ± 5.1 mm in this category of patients. These included 2 patients with Goel type A BI[†] and 3 patients with Goel type B BI[‡].

[§]Group I vs. group II. ^{||}Goel type A BI vs. Goel type B BI.

BI patients was 5.07 ± 4.19 mm. This difference was also statistically highly significant ($p = 0.004$). Thus, the distance of odontoid tip from the P-IOP line was significantly different in the BI versus non-BI patients, and in Goel types A and B BI patients (Table 2).

3) Cutoff point for diagnosis of BI

Analysis of area under the ROC curve used for patients diagnosed as BI by calculating the distance between the odontoid tip and P-IOP line yielded area under the curve (AUC) of 0.853 ($p < 0.001$) (95% confidence interval [CI], 0.803–0.902). The ROC analysis identified 9.0 mm (8.92–9.15 mm) as the cut-point for diagnosis of BI using the P-IOP line as reference from the tip of odontoid process, with a sensitivity of 77%–80% and specificity of 87%–80% (Table 3, Fig. 5). The inference was that if odontoid tip was at a distance of < 9 mm below the P-IOP line, it was suggestive of BI.

4) Correlation between Chamberlain and P-IOP line

A comparison of the distance of odontoid tip to the P-IOP line and the Chamberlain line for establishing the diagnosis BI

Table 3. Cutoff values (area under the curve analysis) of the distance between the tip of odontoid and the P-IOP line for the diagnosis of BI and their respective sensitivity and specificity

Cutoff value (mm)	Sensitivity (%)	Specificity (%)	AUC	95% CI	p-value
Total patients with BI (n = 84)*			0.853	0.803–0.902	< 0.001
7.14	58.3	91.1			
8.99	76.2	79.3			
9.56	79.8	76.0			
9.69	81	73.7			
12.3	92.9	50.3			
Patients with Goel type A BI (n = 64)†			0.837	0.781–0.894	< 0.001
8.99	73.4	79.2			
9.07	75.4	78.7			
10.75	87.5	64			
11.30	90.6	59.6			
11.95	92.2	56.2			
Patients with Goel type B BI (n = 20)‡			0.886	0.807–0.964	< 0.001
6.66	70	92.1			
6.83	75	91.6			
8.99	80	80.2			
11.0	85	62.4			
11.35	95	59.9			

The chances of BI increasing when distance value is \leq cutoff value.

P-IOP, posterior tip of the hard palate to the internal occipital protuberance; BI, basilar invagination; AUC, area under the curve; CI, confidence interval.

The mean distance was significant lower in the cases (patients with BI) than control group ($p < 0.05$). To diagnosis the BI from the measured distance (between the tip of odontoid and the P-IOP line), receiver-operating characteristic (ROC) curve analysis was used. ROC curve yielded that diagnostic accuracy of the distance was 85.3% (AUC = 0.853; 95% confidence interval, 0.803–0.902; $p < 0.001$). Similarly, diagnostic accuracy of the patients with Goel type A BI and Goel type B BI were 83.7% (AUC = 0.837; 95% CI, 0.781–0.894; $p < 0.001$) and 88.6% (AUC, 0.886; 95% CI, 0.807–0.964; $p < 0.001$), respectively.

ROC analysis identified that cutoff value 8.99 mm as the cut-point for diagnosis of BI using the P-IOP as reference from the tip of odontoid process, with a sensitivity in range of 73.4%–80% and specificity of 79.2%–80.2%.

*Five patients belonging to group I had the tip of odontoid being higher than the P-IOP line. These patients were classified as the 'very high BI' group. They were excluded from this analysis. The mean distance of the tip of the odontoid process above the P-IOP line was 6.47 ± 5.1 mm in this category of patients. These included 2 patients with Goel type A BI† and 3 patients with Goel type B BI‡.

(using Spearman rho correlation test) revealed a significant negative correlation (correlation coefficient = -0.39, $p = 0.002$) in these patients.

The Chamberlain line measures the distance of odontoid tip relative to the line joining posterior tip of hard palate to opisthion. A critical assessment of these landmarks in 114 patients with the group I patients with BI revealed that in 64 patients with an occipitalised atlas, the opisthion and basion could not be clearly defined. In a few patients, neck tilt and rotation (due to which the midsagittal reconstructed CT scan and MRI did not demonstrate both the landmarks in the midsagittal plane) was the confounding factor that affected the actual delineation of Chamberlain line. This inability to correctly localise the opis-

thion while measuring the Chamberlain line was more pronounced in type B BI where, in 15 out of 23 patients, the opisthion could not be well-delineated.

5) Assessment of CL and OL

In group I patients with BI, the mean CL was 32.9 ± 5.5 mm (range, 19.6–44.2 mm) and the mean OL was 36.9 ± 7.2 mm (range 16.6–54.3 mm). In the group II control patients, however, the CL was 32.09 ± 6.7 mm (range, 15.4–59.9 mm) and the mean OL was 37.05 ± 5.4 mm (range, 19.8–50.3 mm). The COV in group I patients for CL was 16.9% and OL was 19.5%. In comparison, the COV in group II patients for CL was 21% and for OL was 14.7%. Overall, there was nearly a 15%–20% variability

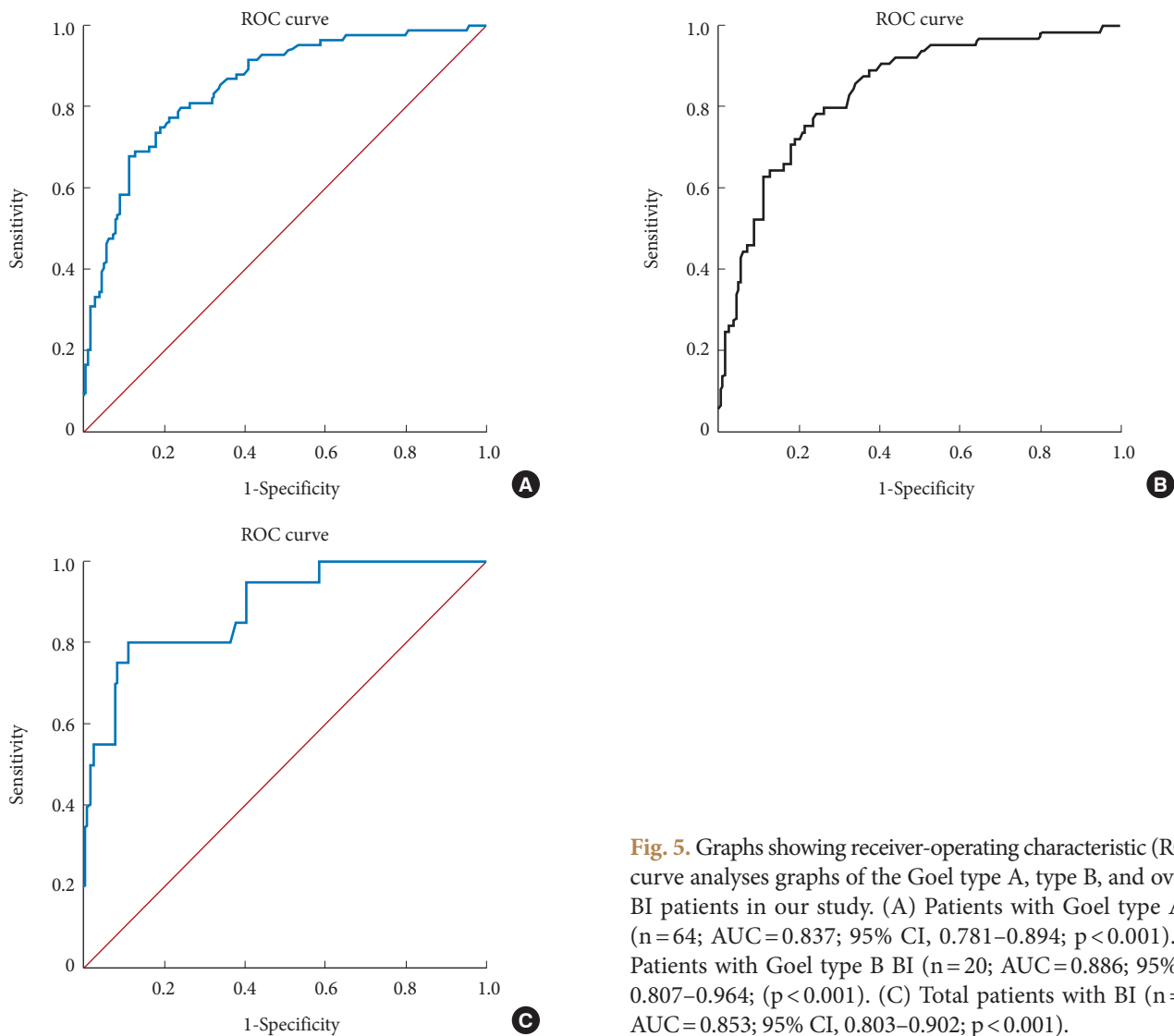


Fig. 5. Graphs showing receiver-operating characteristic (ROC) curve analyses graphs of the Goel type A, type B, and overall BI patients in our study. (A) Patients with Goel type A BI ($n=64$; $AUC=0.837$; 95% CI, 0.781–0.894; $p<0.001$). (B) Patients with Goel type B BI ($n=20$; $AUC=0.886$; 95% CI, 0.807–0.964; ($p<0.001$). (C) Total patients with BI ($n=84$; $AUC=0.853$; 95% CI, 0.803–0.902; $p<0.001$).

for these parameters among patients.

6) Factors affecting the diagnosis of BI using P-IOP line

A binary logistic regression analysis was used to assess the impact of clinicoradiological factors on the distance (between odontoid tip-P-IOP line). In univariate analysis, the results showed that the cervicomedullary angle ($p=0.038$) as well as the distance of odontoid tip to Chamberlain line ($p=0.019$) were significant associated with BI, whereas variables including the patient's age ($p=0.067$), srx ($p=0.125$), platybasia ($p=0.284$), CL ($p=0.211$), OL ($p=0.885$), and extent of tonsillar descent from foramen magnum ($p=0.579$) did not have any association. In multivariate analysis, out of the 2 variables found to be significant ($p<0.05$) in univariate analysis, only the distance of odontoid tip to Chamberlain line (value adjusted odds ratio, 1.41;

95% CI, 1.06–1.85; $p=0.017$) was significant and cervicomedullary angle was insignificant (value adjusted odds ratio, 0.96; 95% CI, 0.90–1.02; $p=0.268$).

DISCUSSION

1. Strengths of the Proposed Parameter

The foremost strength of the proposed measurement (the distance between odontoid tip-P-IOP line ≤ 9 mm) lies in its highly significant ($p<0.001$) ability to establish the presence of BI in comparison to the control population with no BI. The second advantage of utilizing this craniometric parameter for the diagnosis of BI is in incorporating clearly distinguishable midsagittal imaging standard landmarks (posterior tip of the hard palate, internal occipital protuberance, and tip of odon-

toid), that are accessible across all relevant imaging modalities, including midsagittal images of CT and MRI scans. As these landmarks are distinguishable as fairly broad ridges having a uniformly horizontal level on the skull, they may be well-localised even in the presence of neck tilt or rotation, where midsagittal and parasagittal images may be seen in the same plane. This is in contradiction to the conventional landmarks, such as the opisthion and basion (in the case of McRae line and Chamberlain line) and the inferior-most point on the occipital squama (in the case of McGregor line), that may occasionally be difficult to determine in the presence of an occipitalised atlas. Moreover, neck tilt and rotation (due to the asymmetrical facet joints or condylar hypoplasia) that often accompany BI, have 2 adverse effects in delineating the landmarks utilized in the conventional parametric lines. The first is that the mastoid and/or the C1–2 facet joint may overlap with the basion and opisthion on the transtable lateral x-ray imaging of the CVJ. The second is that the foramen magnum margins on the 2 sides may not be at the same level. The neck rotation also results in the opisthion and basion being placed in different parasagittal planes. The inferior-most margin of the occipital squama is also likely to change, based upon the degree of rotation of the patient's head during the midsagittal CT and MRI scan imaging. In the presence of Chiari malformation where the opisthion is difficult to determine, or when a posterior decompression (with or without stabilization) has already been performed, the proposed parameter remains relevant for diagnosing BI, whereas the conventional lines and landmarks cannot be used to establish BI.

The third advantage is that, based upon the P-IOP line, it was possible to distinguish our patients with BI into 2 distinct categories: those with a regular BI, where the tip of odontoid is ≤ 9 mm below the P-IOP line; and those with a very high BI, where the tip of odontoid is higher than the P-IOP line. The 5 patients with a very high BI were associated with platybasia, condylar as well as atlantal facet hypoplasia, and occipitalised atlas. The fourth and the perhaps the greatest advantage is the universal capability of this craniometric parameter to diagnose both varieties of BI, the Goel types A and B BI ($p=0.04$). In the present study, the odontoid tip-P-IOP line distance was, in fact, significantly lesser in patients with Goel type B BI (5.07 ± 4.19 mm) when compared to those with Goel type A BI (7.01 ± 3.78 mm), making the parameter extremely accurate to also diagnose Goel type B BI. The assessment of the distance of odontoid tip-P-IOP line had a 90% accuracy with 80% sensitivity and 81% specificity for establishing the diagnosis of Goel type B BI in the present study.

2. Reason for Choosing the P-IOP Line to Diagnose BI

The position of the IOP remains relatively constant relative to rest of the skull. However, approximately a 15%–20% greater variability for the CL and OL was found among patients with BI in the present study, when compared to patients in the control group. This variability was demonstrable in patients in both Goel types A and B BI categories, respectively. The variability implies that the position of opisthion and basion (which are the landmarks used in the conventional parametric lines) may change in different patients even when the tip of the odontoid process is causing cervicomedullary compression at the same point on the neuraxis. The presence of a smaller posterior fossa with associated platybasia (with shorter CL and OL lines) is the main reason why the conventional parameters fail to diagnose Goel type B BI despite the relative position of the odontoid causing the cervicomedullary compression being at the same site as in Goel type A BI. Menezes¹⁴ also found a significant variability in the incidence of BI, when the latter was diagnosed using different conventional reference lines. In the proposed parameter of the distance between odontoid tip-P-IOP plane to diagnose BI, as the relative positions of the tip of hard palate and internal occipital protuberance remain fairly constant.

Thus, the parameter is a reliable index of the actual *in vivo* position of the odontoid tip relative to the cervicomedullary neuraxis. The comparison of distance of odontoid tip to P-IOP line and Chamberlain line for establishing the diagnosis of BI revealed a significant negative correlation (correlation coefficient = -0.39 , $p=0.002$) and establishes that the proposed parameter may be used as an equally sensitive marker to diagnose BI.

3. How Was the Cutoff Parameter for the Diagnosis of Regular BI Determined?

Table 3 shows the cutoff values (AUC) of the odontoid tip to P-IOP line distance for establishing the diagnosis of BI, and their respective sensitivity and specificity. It was found in a total of 84 patients with regular BI (where the tip of odontoid was below the P-IOP line), the maximum cutoff distance of 9.0 mm had a sensitivity in range of 77%–80% and specificity of 80–87%. In 64 patients with Goel type A BI, the corresponding maximum cutoff distance with the highest sensitivity (75.4%) as well as specificity (78.7%) was 9.07 mm; and, in 20 patients with Goel type B BI, the corresponding maximum cutoff distance with the highest sensitivity (80%) as well as specificity (81%) was 8.92 mm. The ROC analysis, therefore, identified 9.0 mm to be the cutoff maximum distance from the tip of the odontoid to the reference P-IOP line that could be used for the establishment

of the diagnosis of BI.

4. Factors Influencing the Diagnosis of BI Using P-IOP Line

The logistic regression analysis revealed that age, cervicomedullary angle and platybasia had a significant impact ($p < 0.05$) on the distance of odontoid tip from the P-IOP line. Several studies have previously validated that in patients in a higher age group, a greater extent of BI is seen.¹⁴ Resorptive changes leading to condylar and facetar hypoplasia and cranial settling; and, accompanying ligamentous laxity, are the likely explanations for this observed phenomenon. The cervicomedullary angulation inevitably increases based upon a greater degree of posteriorly directed orientation of the tip of odontoid. The perpendicular distance of the odontoid tip from the P-IOP line, in turn, increases in conjunction with a greater posterior angulation of the tip of odontoid towards the cervicomedullary junction. The presence of platybasia (and the often accompanying condylar hypoplasia) further accentuates BI as well as the cervicomedullary angulation.

5. Limitations of the Study

In the presence of neck tilt and torticollis, there may be difficulty in defining the IOP in a few patients with torticollis. Usually, the IOP is a small horizontal ridge and its position is easily detectable even if the scan is showing slightly parasagittal view at places due to torticollis. The posterior tentorial attachment to the IOP may be followed on MRI and on 3D reconstructed CT imaging to define the exact location of IOP. An interobserver bias in measuring the proposed parameter may be another limitation of the study. To overcome this bias, each patient analysed was independently evaluated by 2 groups of observers (2 radiologists and 2 neurosurgeons). The position of the hard palate may vary occasionally, especially in the rarely encountered pediatric patients with midfacial bony anomalies. This possibility was eliminated by including in this study, patients greater than 17 years of age (as complete mineralisation and fusion of tip of odontoid process to the body occurs by 12 years; and the spheno-occipital synchondrosis ossifies by 17 years so that the clivus stops growing in length after that age). The objective of this study was to describe and assess the use of new radiological parameters for the diagnosis of BI. The clinical assessment and correlation between Goel types of BI diagnosed with the P-IOP line and severity of the disease would be a part of a subsequent study.

CONCLUSION

The distance of tip of odontoid to the P-IOP line is recommended as a highly applicable criterion to establish the diagnosis of BI on midsagittal CT and MRI images. This parameter has the capability to establish the diagnosis in both Goel types A and B BI (whereas, the conventional craniometric lines are often unable to unequivocally establish the diagnosis of Goel type B BI). Based upon the height of the tip of odontoid relative to the P-IOP line, 2 types of BI are proposed (regular BI, when the tip of odontoid is < 9.0 mm below the P-IOP line; and, very high BI, when the tip of odontoid is above the P-IOP line), with significant management-related implications.

CONFLICT OF INTEREST

The authors have nothing to disclose.

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