Anatomical Diversity & Bilateral Symmetry: CT-Based Native Acetabular Surface Characterization in Pakistani Adults.

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ABSTRACT:

Objective: The contralateral acetabulum serves as a reliable internal anatomical reference for evaluating pelvic and hip morphology. At the population level, however, bilateral symmetry may coexist with considerable inter-individual variation. This study quantified right-left differences in native acetabular morphology and characterized selected morphometric variants within a multicenter adult Pakistani population.

Methodology: Retrospective cross-sectional analysis of the CT examinations was conducted from January 2023 to December 2024, from three tertiary care hospital. Eligible were adults aged 18-75 years, who had both acetabula and proximal femora completely visible. Examinations that had fractures, prior hip surgery or arthroplasty, developmental dysplasia, advanced OA, destructive arthropathy, femoral-head collapse, a tumor of the pelvis, congenital deformity, substantial pelvic rotation, incomplete visualization or poor image quality were excluded. The maximum acetabular diameter, depth, depth-to-diameter ratio, anatomical anteversion, inclination, lateral center-edge angle and wall indices were measured with a standardized multiplanar CT assessment. The main analysis was a comparison between paired measurements from the right and left side. Secondary analyses involved describing sex-associated differences and the incidence of selected morphometric categories.

Results: Two hundred and four subjects and 408 acetabula were included in the study. The measurements of the acetabula of both the right and left side were comparable. Maximum diameter was 52.1±3.6 mm on the right and 51.9±3.6 mm on the left, with a mean paired difference of 0.20 mm (p=0.126). Differences were similarly small for depth (0.17 mm; p=0.141), depth-to-diameter ratio (0.18 percentage points; p=0.339), anteversion (0.31°; p=0.174), inclination (0.22°; p=0.263), and lateral center-edge angle (−0.19°; p=0.491).

Although this is bilaterally symmetrical, there was morphometric variation with 14.0 % hips with a diameter <48 mm, 22.5 % hips with a depth-to-diameter ratio (DDR) <45, 15.2 % hips with anteversion >25°, 8.3 % hips with inclination >50° and 8.6 % hips with a lateral centre-edge angle (CEA) <25°. For several variants, a significant difference between sexes was observed.

Conclusions: CT-based measurements of the acetabulum demonstrated good bilateral symmetry across all major parameters. However, this symmetry was observed within a population characterized by substantial inter-individual and sex-related anatomical variation. Consequently, native morphology alone may be insufficient to define an individual's hip anatomy, and the contralateral acetabulum may serve as a more reliable patient-specific reference.

Keywords: Bilateral symmetry, acetabulum, computed tomography, pelvic morphology, anatomical variation, hip, anteversion, acetabular depth, and center-edge angle.

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Introduction:

A very basic characteristic of human skeletal structure is bilateral symmetry. This symmetry can also be beneficial in clinical imaging as the healthy side may serve as an "internal standard" to interpret the anatomy of a diseased or surgically altered side. The acetabulum is a three-dimensional structure with multiple dimensions being interdependent: size, depth, orientation and coverage.[1] When right and left acetabula are very similar, the other side may help with the expectations of what the normal anatomy should look like. This comparison might be helpful if there is structural change or when normal anatomy is hard to reconstruct. Bilateral symmetry means that both halves of the body are alike, but does not indicate uniformity within the population.[2] A population can have very small right-left differences, but can also include persons with very different acetabular dimensions or orientations. This distinction is clinically relevant as population reference values do not apply to patient-specific anatomy. CT is an opportunity to examine both acetabular morphology and at the same time.[3] Laterality can be measured within the individual by paired measurements, and the entire set of measurements are used to define the range and the frequency of morphometric variants. The aim of the present study was thus to examine the issue in a bilateral symmetric way.[4] First, the differences in the right and left acetabular dimensions, proportions, orientation and lateral coverage were quantified. The level of clinical significance of such clinically relevant morphometric variants was then studied, and whether the distribution of these variants varied by sex.[5] The hypothesis was not that all individuals would have the same right

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and left acetabula, but that the magnitude of systematic laterality would be less than that of the more general anatomical differences that would be seen between individuals.[6]

Methodology:

This retrospective cross-sectional study that was carried out in three tertiary care hospitals of Pakistan, in the departments of anatomy, radiology and orthopedic surgeries. The CT scans from January 2023 to December 2024 were reviewed in a retrospective manner. The ethics committees of the respective institutions approved the study. Individual informed consent was not required due to the fact that the investigation consisted of CT examinations that were already acquired and not administered as part of the investigation. All procedures followed the ethical principles of the Declaration of Helsinki. The acetabula and proximal femora were included in CT scans of the entire pelvis and adults aged 18–75 years were eligible. When abdominal, pelvic, urological and/or other clinical indications required examinations, these were performed consecutively and screened. Pelvic or acetabular fractures, previous hip surgery, hip arthroplasty, developmental dysplasia of the hip, advanced OA, destructive arthropathy, collapse of the femur head, pelvic tumor, congenital deformity, and poor image quality, extensive pelvic rotation and incomplete visualization of either acetabulum were excluded from the examinations. Multiple exams were available for some individuals, and the earliest exam was chosen. The final study population consisted of 204 subjects and 408 acetabula with 204 right-left pairs.

Sample-size considerations:

The power was computed for the original sample size to show a clinically important difference between the acetabular anteversion of men and women at 5% significance level with 80% power. Correlation between bilateral measurements, incomplete imaging and missing data were taken into account. A minimum of 184 participants was required with about 10% more being added because there was a possibility that some measurements were incomplete, yielding a total of 204 participants. The current manuscript examines primarily bilateral morphology, but the paired cohort of children resulted in 204 right-left comparisons. The acquisition and orientation of CT. The CT examinations were obtained with the participants in supine position, with the lower limbs in neutral rotation. Reconstructions made from 1-3 mm slices were accepted. Before assessment, the DICOM datasets were anonymized.[7] The multiplanar reconstruction and conventional bone-window settings were employed. The pelvis was re-oriented to the anterior pelvic plane which was created by the anterior superior iliac spines and pubic tubercle.

Morphometric assessment Max acetabular diameter measured in the plane, which exhibited the greatest opening, between the superior and inferior acetabular margins. The depth of the acetabulum was measured perpendicular from the center of the acetabular opening line to the deepest point of the acetabular fossa.[8] The acetabular depth to diameter ratio was determined by dividing the acetabular depth by the maximum acetabular diameter and multiplying by 100. Anatomical anteversion was determined on the axial plane which crosses both centers of the femoral heads, and was defined as the angle between the line of the acetabular opening and the sagittal line of the pelvis.[9] The angle between the acetabular opening line and the horizontal pelvic reference was used to measure acetabular inclination on the coronal plane. Lateral center-edge angle was the angle between a vertical line through the center of the femoral head and a line from the center of the femoral head to the lateral acetabular rim. The anterior and posterior wall indices were defined as the distance from the center of the femur head to the anterior and posterior walls, respectively, divided by the radius of the femur head.

Results:

The description and the clinical categories used for the measurements are summarized in Table 1, “CT Measurement Definitions and Morphometric Categories Used to Characterize Native Acetabular Anatomy.” Morphometric variation categories Maximum diameter was defined as small (< 48 mm), intermediate (48 to 55 mm) or large (> 55 mm) for descriptive analysis. Acetabular depth <23 mm was defined as shallow and a depth-to-diameter ratio <45% as reduced. Anteversion was categorized as <10°, 10–25°, or >25°. Inclination was categorized as <35°, 35–50°, or >50°. Lateral center-edge angle was categorized as <25°, 25–39°, or ≥40°. These thresholds were used to describe morphometric variation within the cohort. Statistical analysis Main analysis involved a comparison of right and left acetabular values within the participants using paired analysis. Mean values, mean paired differences and p-values were presented.

Table I. CT Measurements and Their Relevance to Total Hip Arthroplasty.

Parameter	Measurement method	Study category	Relevance to THA
Maximum diameter	Greatest acetabular opening	Small <48 mm; intermediate 48–55 mm; large >55 mm	Preliminary cup-size selection
Depth	Opening line to deepest acetabular point	Shallow <23 mm	Reaming depth and medial wall preservation
Depth-to-diameter ratio	Depth/ diameter ×100	Reduced <45%	Component containment
Anatomical anteversion	Axial acetabular opening angle	<10°, 10-25° or >25°	Cup version and wall coverage
Inclination	Coronal acetabular opening angle	<35°, 35-50° or >50°	Superior coverage and edge loading
Lateral centre-edge angle	Head centre to lateral rim	<25°, 25-39° or ≥40°	Lateral femoral -head coverage
Anterior wall index	Anterior wall distance/head radius	Continuous measurement	Anterior support and cup overhang
Posterior wall index	Posterior wall distance/head radius	Continuous measurement	Posterior support and stability

Selected morphometric categories were compared between male and female hips by means of secondary analyses. Multivariate relationships involved sex, age, and study center with diameter, anteversion, and inclination also were explored as provided in the analysis. A two sided p value of < 0.05 was deemed as statistically significant. Results Cohort characteristics.

A total of 204 adults (110 males and 94 females) participated in the study. Mean age was 45.7±14.1 years. The mean age was 46.5±14.0 years among men and 44.8±14.2 years among women. The age distribution consisted of 71 partici-

pants aged 18-39 years (34.8%), 86 aged 40-59 years (42.2%), and 47 aged 60-75 years (23.0%). A total of 75 participants were recruited in Centre A (36.8%), 68 participants were recruited in Centre B (33.3%) and 61 participants were recruited in Centre C (29.9%). CT slice thickness was ≤1.5 mm in 142 examinations (69.6%) and >1.5-3 mm in 62 examinations (30.4%). The demographic distribution and CT acquisition characteristics of the study cohort (N=204) are shown in Table 2.

Table No 2. Characteristics of the Study Participants (N=204).

Characteristic	Overall	Men (n=110)	Women (n=94)
Age, years	45.7±14.1	46.5±14.0	44.8±14.2
18-39 years	71 (34.8)	36 (32.7)	35 (37.2)
40-59 years	86 (42.2)	48 (43.6)	38 (40.4)
60-75 years	47 (23.0)	26 (23.6)	21 (22.3)
Centre A	75 (36.8)	41 (37.3)	34 (36.2)
Centre B	68 (33.3)	37 (33.6)	31 (33.0)
Centre C	61 (29.9)	32 (29.1)	29 (30.9)
Slice thickness ≤1.5 mm	142 (69.6)	77 (70.0)	65 (69.1)
Slice thickness >1.5-3 mm	62 (30.4)	33 (30.0)	29 (30.9)

Primary analysis: symmetry of the acetabular bones bilaterally Dimensional symmetry. The main analysis of this study was the comparison between the right and left acetabular measurements within the same subjects.

Table No 3. Paired Comparison of Right and Left Acetabula (N=204 Pairs).

Measurement	Right side	Left side	Mean paired difference	p-value
Maximum diameter, mm	52.1 ±3.6	51.9 ±3.6	0.20	0.126
Depth, mm	25.2 ±2.7	25.0 ±2.7	0.17	0.141
Depth-to-diameter ratio, %	48.4 ±4.5	48.2 ±4.5	0.18	0.339
Anteversion, degrees	19.1 ±6.4	18.8 ±6.3	0.31	0.174
Inclination, degrees	42.8 ±5.5	42.6 ±5.5	0.22	0.263
Lateral center -edge angle, degrees	34.7 ±6.4	34.9 ±6.3	−0.19	0.491

Within-Participant Right-Left Comparison of Acetabular Morphometry (204 Pairs) is provided in Table 5. The maximum acetabular diameter was 52.1mm ± 3.6 mm (right) and 51.9mm ± 3.6 mm (left). The mean paired difference was 0.20 mm and did not show any statistically significant difference (p=0.126). The mean depth of the acetabular on the right and left sides was 25.2 mm ± 2.7 and 25.0 mm ± 2.7, respectively. The mean paired difference was 0.17 mm (p=0.141). The depth-to-diameter ratio was also approximately equal on both sides (48.4±4.5% on the right and 48.2±4.5% on the left). The mean paired difference was 0.18 percentage point (p=0.339). These results suggest that at the cohort level, there was a close similarity of the main dimensions of the acetabulum between right and left sides. Bilateral orientation This was the same for acetabular orientation. The mean right-sided anteversion was 19.1±6.4°, which was similar to the mean left-sided anteversion of 18.8±6.3°. The mean paired difference was 0.31° (p=0.174). Mean inclination was 42.8±5.5° on the right and 42.6±5.5° on the left, with a paired difference of 0.22° (p=0.263). The lateral center-edge angle was 34.7±6.4° on the right and 34.9±6.3° on the left. The mean paired difference was −0.19° (p=0.491). Therefore, there was no statistically significant systematic right-left difference for any dimensional, proportional, angular or lateral coverage parameter. There is also anatomical diversity, despite the bilateral symmetry. In addition there exists anatomical diversity despite the bilateral symmetry. The bilateral analysis only gives one aspect of the data. The second is the range of variation between different individuals.

Table No 4. Acetabular Measurements According to Sex (408 Hips).

Measurement	Overall	Men (220 hips)	Women (188 hips)	Adjusted difference*	p-value
Maximum diameter (mm)	52.0± 3.6	54.1 ±2.9	49.6±2.8	4.39 (3.85-4.93)	<0.001
Depth (mm)	25.1± 2.7	26.2 ±2.5	23.8±2.3	2.29 (1.83-2.75)	<0.001
Depth-to-diameter ratio, %	48.3± 4.5	48.5 ±4.4	48.0±4.6	0.43 (−0.44-1.30)	0.332
Anteversion, degrees	18.9± 6.3	17.4 ±5.8	20.6±6.4	−3.14 (−4.30 to −1.98)	<0.001
Inclination, degrees	42.7± 5.5	42.0 ±5.2	43.5±5.7	−1.42 (−2.46to −0.38)	0.008
Lateral center-edge angle, degrees	34.8± 6.4	35.6 ±6.2	33.9±6.5	1.61 (0.40-2.82)	0.009
Anterior wall index	0.36± 0.08	0.35 ±0.08	0.37±0.08	−0.02 (−0.04 to −0.01)	0.011
Posterior wall index	0.93± 0.13	0.94 ±0.13	0.92±0.14	0.02 (−0.01-0.05)	0.194

The acetabular morphometric measurements are given separately by sex in Table 3, “Acetabular Morphometric Measurements according to Sex (408 Hips).” Overall, the mean maximum acetabular diameter was 52.0±3.6 mm, with men having a mean diameter of 54.1±2.9 mm and women of 49.6±2.8 mm. The adjusted difference associat-

ed with female sex was −4.39 mm (95% CI −4.93 to −3.85; p<0.001). There was also a difference in depth between the sexes, with the mean depth of 26.2±2.5 mm in males compared to 23.8±2.3 mm in females. The adjusted difference was −2.29 mm for female sex (95% CI −2.75 to −1.83; p<0.001). In contrast, the depth-to-diameter ratio was similar between men and women (48.5±4.4% vs 48.0±4.6%; p=0.332). Women demonstrated greater anteversion (20.6±6.4° vs 17.4±5.8°; adjusted difference 3.14°, 95% CI 1.98-4.30; p<0.001) and greater inclination (43.5±5.7° vs 42.0±5.2°; adjusted difference 1.42°, 95% CI 0.38-2.46; p=0.008). Men demonstrated a greater lateral center-edge angle (35.6±6.2° vs 33.9±6.5°; adjusted difference 1.61°, 95% CI 0.40-2.82; p=0.009). Anterior wall index was found to differ between gender while there was no significant difference seen in the posterior wall index. How often storms of a specific magnitude occur.

Table No 5. Distribution of Clinically Relevant Acetabular Variations.

Variation	Overall hips, n (%)	Male hips, n (%)	Female hips, n (%)	p-value*
Diameter <48 mm	57 (14.0)	7 (3.2)	50 (26.6)	<0.001
	64 (15.7)	56 (25.5)		
	70 (17.2)	21 (9.5)		
Depth-to-diameter ratio <45%	92 (22.5)	47 (21.4)	45 (23.9)	0.526
Anteversion <10°	29 (7.1)	20 (9.1)	9 (4.8)	0.087
Anteversion >25°	62 (15.2)	21 (9.5)	41 (21.8)	<0.001
Inclination >50°	34 (8.3)	13 (5.9)	21 (11.2)	0.047
Lateral center-edge angle <25°	35 (8.6)	13 (5.9)	22 (11.7)	0.034

The frequency of the extreme morphometric events. Data for the selected categories of morphometric variants are shown in Table 4, Distribution of Selected Clinically Relevant Acetabular Morphometric Variants (408 Hips). In 57 hips, there was a maximum acetabular diameter < 48 mm (14.0%). Of these there were 7 male hips (3.2%) and 50 female hips (26.6%) which was significant (p<0.001) between male and female. A depth-to-diameter ratio <45% occurred in 92 hips (22.5%), including 47 male hips (21.4%) and 45 female hips (23.9%; p=0.526). No statistically significant difference in sex was found for hips with anteversion <10° (29 hips, 7.1% of hips, 9.1% of male hips vs 4.8% of female hips; p=0.087). Anteversion >25° occurred in 62 hips (15.2%), including 21 male hips (9.5%) and 41 female hips (21.8%; p<0.001). Inclination >50° was observed in 34 hips (8.3%), affecting 13 male hips (5.9%) and 21 female hips (11.2%; p=0.047). A lateral center-edge angle <25° occurred in 35 hips (8.6%), including 13 male hips (5.9%) and 22 female hips (11.7%; p=0.034). These results show that although there was a bilaterally symmetric structure at the group level, there was still considerable variation in the morphology of the individual hips. Multivariable assessment.

Table No 6. Multivariable Associations with Selected Acetabular Measurements.

Predictor	Diameter, β (95% CI), mm	Anteversion, β (95% CI), degrees	Inclination, β (95% CI), degrees
Female sex	- 4.39 (- 4.93 to - 3.85)	3.14 (1.98-4.30)	1.42 (0.38-2.46)
Age per 10 years	- 0.09 (- 0.27-0.09)	0.47 (0.11-0.83)	0.32 (0.01-0.63)
Centre B versus Centre A	0.21 (- 0.46-0.88)	- 0.39 (- 1.70-0.92)	0.44 (- 0.73-1.61)
Centre C versus Centre A	- 0.30 (- 1.01-0.41)	0.63 (- 0.76-2.02)	- 0.37 (- 1.62-0.88)

The multivariable associations of sex, age, and study center for selected acetabular measurements are presented in Table 6, “Multivariable Associations of Sex, Age, and Study Center With Selected Acetabular Measurements.” Female sex was associated with a −4.39-mm coefficient for diameter (95% CI −4.93 to −3.85), a +3.14° coefficient for anteversion (95% CI1.98-4.30), and a +1.42° coefficient for inclination (95% CI 0.38-2.46). Age per 10 years had a coefficient of −0.09 mm for diameter (95% CI −0.27 to 0.09), 0.47° for anteversion (95% CI 0.11-0.83), and 0.32° for inclination (95% CI 0.01-0.63).

Discussion:

This work brings to the fore the coexistence of high levels of bilateral symmetry and anatomical diversity, the central finding of this work. Both the mean diameters and depths of right and left acetabula were very similar, as were the proportional depths, anteversion, inclination, and lateral center-edge angles. There was no statistically significant difference in any of the six main paired comparisons. The group was not a morphologically homogeneous one at the same time. Significant differences occurred between different patients, particularly in acetabular size and orientation.10 These findings, therefore, imply two seemingly contradictory but complementary results; the first is that the two halves of the pelvis were fairly alike within individuals and the second is that individuals could have significant differences in their acetabular anatomy. Bilateral symmetry, an anatomical reference. The differences observed were a small right-left difference. The difference between the two maximum diameter was only 0.20 mm while the overall standard deviation was about 3.6 mm. The average difference in anteversion was 0.31° with a standard deviation greater than 6°. This difference implies that the systematic variation among the cohort was relatively low and was mostly due to other factors than to side.11 The discovery could have implications for the interpretation of images. If the shape of one acetabulum is altered, the other may serve as a patient-specific reference for the normal morphology. This principle can be important in reconstructive surgery and in assessing and understanding the nature of unilateral pathologies.

The current analysis does not, however, establish similarity of groups but similarity between individuals. A future study with limits of agreement or individual paired differences would better be suited to assess the ability of one side to predict the other side in individual patients. Symmetry does not necessarily mean uniformity. Another important finding is that bilateral similarity did not take away a great deal of

interindividual variation. Almost one quarter (14%) had a maximum diameter <48 mm and almost one half (45%) had a depth to diameter ratio <45%. Over 15% had an anteversion greater than 25%. The results suggest that the population mean is not sufficient to represent the acetabular anatomy.

This can be seen from the sex-stratified data. The acetabular dimensions were larger in males and inclination and anteversion were larger in females, but there were no significant differences in the other measures. This difference in the maximum diameter was most marked. In the female hips, 26.6% had a diameter <48 mm, as compared to 3.2% of male hips. The size of the acetabula was thus highly sex -specific, despite the high similarity between right and left sides of each pair. Comparing the size of things relative to their proportions. One of the more educational results was the distinction between absolute and relative configuration. The maximum diameter and shallower acetabula were smaller in women. However, the sex difference was virtually the same in both the depth-to-diameter ratio and the mid-shaft circumference. This indicates that the morphology of the acetabulum can't be defined solely as "size. The absolute dimension reflects the physical size of the acetabulum while the depth-to-diameter ratio gives information on the configuration of the acetabulum. Thus, these parameters for anatomical studies should be viewed separately. This is due to the variation in acetabular orientation. The study also showed significant variation in the acetabular orientation. Women's mean anteversion was 3.1° greater than men's and anteversion >25° was seen in 21.8% of the female hips versus 9.5% of the male hips. In the same way, more women had a higher inclination (>50°). The results of this finding indicate that acetabular dimension differences are not the only factors contributing to population heterogeneity; three-dimensional orientation is also a factor. Importantly, the difference in orientation between the right and left sides was extremely small compared to the difference in orientation between the sexes. This separation strengthens the value of the bilateral design, as if the right and left sides of the body are comparable but there are clear differences between the sexes, the primary differences are more likely to lie within the individual rather than between the sexes and the body's right and left side.

Lateral coverage: The lateral center-edge angle was also greater among men. A hip hip value <25° was seen in 8.6% of hips overall and more in women. The lateral center-edge angle is a clinically familiar parameter; however, it is important to note that the current study should not be considered as setting thresholds for the diagnosis of acetabular dysplasia. The participants were chosen to avoid the presence of major developmental and degenerative abnormalities and the analysis was planned to describe morphology, not diagnose disease. However, the results show that there is intra-population variation in lateral coverage in an apparently structurally normal population of CT. Implications for the use of contralateral anatomy.

A practical implication of the findings can be drawn for comparative imaging. A single hip affected by disease might be a better reference point than an average for a population. The present results are in agreement with this concept as there was little difference between the right and left sides on all of the principal measurements.12 Concurrently, there is significant population variation; the contralateral side should serve as a patient-specific reference rather than as a testament to all acetabula being built to a standard template. This difference is significant, especially if the non-dominant hip is not normal or if there is a subtle difference in hip anatomy between the two sides.

Multivariable findings Results from the multivariable analysis showed that female sex was still a significant predictor of smaller diameter, higher anteversion and inclination. Slight associations were noted with anteversion and inclination, and a weak association with diameter was noted within the reported confidence interval for age. No clear associations with the selected measurements were found for the center coefficients. This reinforces the other interpretation that the primary patterns were not clearly associated with a single participating institution.

Strengths: This investigation has the advantage of the paired bilateral design. All of the participants provided data from both acetabula, which permitted intra-individual laterality to be assessed. Advantages are the multicenter design, standardized pelvic reorientation, measurement of multiple complementary morphometric parameters and characterization of continuous measures as well as predefined anatomical categories.

Conclusion: In this multicenter Pakistani cohort, the native acetabulum was found to be well bilaterally developed in terms of dimension, proportions, orientation and lateral coverage. This bilateral symmetry, however, co-existed with a great individual and sex-related morphological variability. The results indicate that the contralateral acetabulum can be useful for patient-specific anatomical information but population-averages should be avoided as being representative of individual anatomy. Native acetabular morphology must be described completely, using absolute dimensions, proportional shape, orientation and coverage, and not just a single dimension. These findings should be expanded in the future through quantifying individual level bilateral agreement and establishing the role of the observed anatomical patterns in the process of the preoperative planning, component positioning, or clinical results after hip reconstruction.

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Author's Contribution	
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