Typical Development of the Secondary Ossification Centers of the Acetabulum and Their Effects on Acetabular Coverage of the Femoral Head

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Background: We investigated the normal development of the secondary ossification centers of the acetabulum, focusing on their location and the amount of acetabular coverage increased by them.

Methods: We enrolled 132 patients who were 7 to 16 years of age and had no pelvic deformity but did have ≥1 os ischium, os ilium, and/or os pubis on abdominal or pelvic computed tomographic (CT) scans. The locations of the ossification centers were evaluated by adopting an orientation using 0° for the superior acetabulum, 90° for the anterior acetabulum, 180° for the inferior acetabulum, and 270° for the posterior acetabulum, on a reconstructed 3-dimensional (3D) CT image. The acetabular coverage increase by the os ischium, os ilium, or os pubis was defined as the difference in the posterior acetabular sector angle (ΔPASA), posterosuperior acetabular sector angle (ΔPSASA), superior acetabular sector angle (ΔSASA), anterosuperior acetabular sector angle (ΔASASA), or anterior acetabular sector angle (ΔAASA) measured with and without each secondary ossification center. Patients were grouped into 3 age ranges: late childhood, preadolescence, and early adolescence. The location of each ossification center and the increase in acetabular coverage were compared between these groups.

Results: In the late-childhood group, the median start-to-end positions in right hips were 269° to 316° for the os ischium, 345° to 356° for the os ilium, and 81° to 99° for the os pubis. These positions tended to be wider in the early-adolescence group at 252° to 328° for the os ischium ($p < 0.001$), 338° to 39° for the os ilium ($p = 0.005$), and 73° to 107° for the os pubis ($p = 0.049$) in right hips. In right hips in the late-childhood group, the median values were 8.1° for ΔPASA, 14.0° for ΔPSASA, 9.9° for ΔSASA, 11.1° for ΔASASA, and 3.9° for ΔAASA; and in the early-adolescence group, the median values in right hips were 10.7° for ΔPASA, 12.9° for ΔPSASA, 8.4° for ΔSASA, 7.4° for ΔASASA, and 5.6° for ΔAASA. Only the median ΔPASA was larger in the early-adolescence group than in the late-childhood group ($p = 0.026$). Similar results were observed in left hips.

Conclusions: In early adolescence, the secondary ossification centers appeared at more extended areas along the acetabular rim, and the increase in acetabular coverage by the secondary ossification centers tended to be larger in the posterior area but not in the anterior or superior area.

Level of Evidence: Diagnostic Level III. See Instructions for Authors for a complete description of levels of evidence.

The acetabular cartilage complex in children comprises the medial triradiate and lateral cup-shaped portions interposed between the ischium, ilium, and pubis[1]. During growth, the acetabular diameter is enlarged by interstitial growth within the triradiate cartilage (TRC); simultaneously, the acetabular depth is increased by interstitial growth within the lateral acetabular cartilage complex and appositional growth at the periphery of this complex or the ring apophysis that surrounds the acetabular bones[1]. During preadolescence and adolescence, the secondary ossification centers appear within the ring apophysis of an innominate bone and eventually fuse to form acetabular osseous walls[1-4], which increases the acetabular coverage of the femoral head.

Overcoverage of the acetabulum can cause pincer-type femoroacetabular impingement (FAI), and undercoverage of the acetabulum can cause hip instability. Understanding the temporal changes in the locations of the acetabular secondary ossification centers and the coverage gained by these centers may help to predict whether acetabular deficiency, especially focal acetabular deficiency, will improve naturally, or whether

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acetabular overcoverage will progress to a degree that requires a surgical procedure[5,6]. Therefore, these are essential factors that must be determined by pediatric orthopaedic surgeons and hip specialists. Moreover, because secondary ossification centers can be misdiagnosed as a bone fragment from a traumatic acetabular fracture[7], understanding the development of the acetabular secondary ossification centers is also important for orthopaedic traumatologists and radiologists.

To our knowledge, no study has yet evaluated the exact location of the secondary ossification centers in the acetabulum. A study showed that acetabular coverage increased with the ossification of the posterior acetabular rim[8]. However, the development of each secondary ossification center and its association with acetabular coverage have not yet been adequately studied.

In the current study, we aimed to identify the normal development of the secondary ossification centers of the acetabulum, focusing on their location and contribution to the increase in acetabular coverage.

Materials and Methods

Patients

This retrospective study was approved by the institutional review board of our institution. The clinical data warehouse of a single tertiary-care pediatric center was searched to identify patients who underwent abdominal and pelvic computed tomographic (CT) scans between November 1, 2002, and October 31, 2021. Patients who underwent CT scans at the age of 7 to 16 years due to abdominal pain (n = 523), acute appendicitis (n = 458), inguinal hernia (n = 60), or acute pyelonephritis (n = 52) were included in this study. The age criteria for inclusion were determined on the basis of previous reports on the appearance and closure timing of the secondary ossification centers of the acetabulum[2,9]. To avoid including patients with conditions potentially affecting normal development and hip anatomy, we excluded those with a history of endocrine disorders or hormonal replacement (n = 87); leukemia (n = 72); primary tumors or bone metastases in the pelvis (n = 51); congenital anomalies (n = 27); neuromuscular diseases (n = 22); or pelvic fractures, developmental dysplasia of the hip, or sequelae of septic arthritis of the hip (n = 8). Twenty-six patients whose CT scans were inadequate for hip joint evaluation were also excluded. After reviewing the CT scans of the remaining 800 eligible patients, we excluded 668 patients in whom no distinct os ischium, os ilium, or os pubis could be identified. Based on these criteria, 132 patients (73 male and 59 female) were included in the study cohort (Fig. 1), with a mean age (and standard deviation) of 12.0 ± 1.3 years (range, 9.7 to 14.9 years) for male patients and 11.2 ± 1.1 years (range, 8.5 to 13.0 years) for female patients (Fig. 2). Table I shows the frequency of each ossification center and the age of the patients. There was no significant difference in demographic characteristics, imaging techniques, and acetabular sector angles[10,11] between patients with and without distinct acetabular secondary ossification centers (see Appendix Supplementary Table I).

Imaging Technique

All patients were scanned in the supine position using scanners from various vendors, including the Siemens SOMATOM Definition Flash scanner (n = 32), Toshiba Aquilion ONE (n = 27),

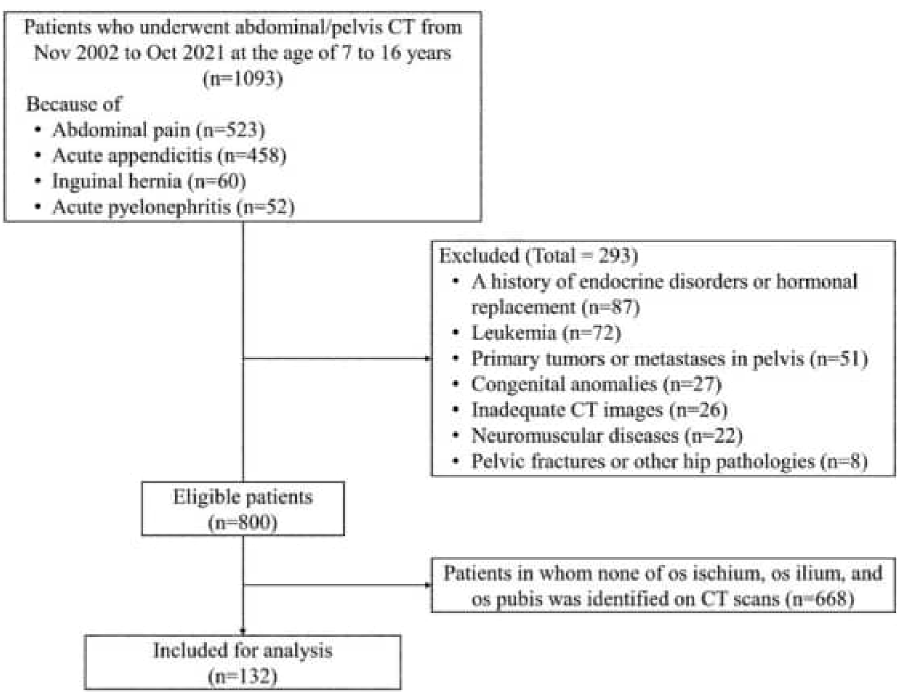

Fig. 1

Flowchart of the study.

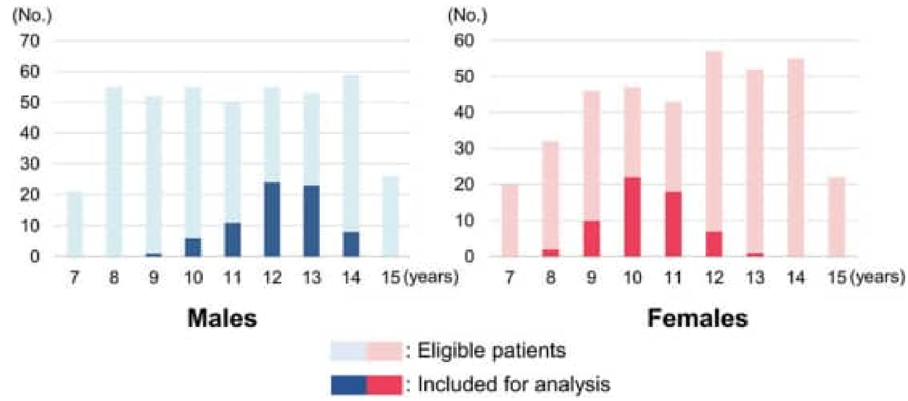

Fig. 2
Bar graph showing the distribution of the eligible and included patients by age and sex. Patients who were expected to have normal development of the pelvis (n = 800) are shown in light blue (male patients) and pink (female patients). Among the eligible patients, 132 with ≥1 secondary ossification center (os ischium, os ilium, and/or os pubis) were identified on CT scans and were included and shown in dark blue (male patients) and (female patients). The proportion of included patients relative to the eligible patients by age shows a similar pattern in male and female patients, with a delay of approximately 1 year in male patients.

Philips Brilliance 64 (n = 26), Siemens Sensation 16 (n = 18), Philips MX8000 (n = 16), Philips Brilliance iCT 256 (n = 8), and Siemens SOMATOM Force scanner (n = 5). The imaging parameters varied according to patients' weight: tube voltage, 70 to 120 kVp; tube current, 14 to 180 mAs; matrix, 512 × 512; and slice thickness, 3 to 5 mm. We reconstructed multiplanar images and 3-dimensional (3D) images from raw DICOM files with PostDICOM Cloud PACS 1.1 (PostDICOM).

Locations of Acetabular Secondary Ossification Centers

First, we reconstructed the 3D pelvic lateral image by digitally removing the femoral head to facilitate the analysis of the acetabulum (Fig. 3). We then drew a best-fit circle over the acetabular rim and defined the center of the circle as the center of the acetabulum. We set the midpoint of the acetabular notch at 180° and the point opposite 180° on a line through the center of the circle as 0°. The anterior aspect of the acetabulum was set at 90° and the posterior

TABLE I Frequency of Each Acetabular Secondary Ossification Center and Corresponding Patient Age

Ossification Center	Male Patients (N = 73)	Female Patients (N = 59)	P Value
Os ischium			
Laterality*			0.994†
Right	67	56	
Left	65	54	
Age on right side‡ *(yr)*	12.5 ± 1.1 (9.7 to 14.9)	10.7 ± 1.0 (8.5 to 13.0)	<0.001§
Age on left side‡ *(yr)*	12.5 ± 1.1 (9.7 to 14.9)	10.7 ± 1.0 (8.5 to 13.0)	<0.001§
Os ilium			
Side*			0.975†
Right	27	24	
Left	30	26	
Age on right side‡ *(yr)*	13.0 ± 1.0 (10.3 to 14.9)	11.3 ± 1.0 (9.1 to 13.0)	<0.001§
Age on left side‡ *(yr)*	13.0 ± 1.0 (10.3 to 14.9)	11.2 ± 0.9 (9.1 to 13.0)	<0.001§
Os pubis			
Laterality*			0.972†
Right	47	35	
Left	47	34	
Age on right side‡ *(yr)*	12.2 ± 1.1 (9.7 to 14.1)	10.5 ± 1.0 (8.5 to 12.6)	<0.001§
Age on left side‡ *(yr)*	12.2 ± 1.1 (9.7 to 14.1)	10.5 ± 1.0 (8.5 to 12.6)	<0.001§

*The values are given as the number of acetabula. †Fisher exact test. ‡The values are given as the mean and the standard deviation, with the range in parentheses. §Student t test.

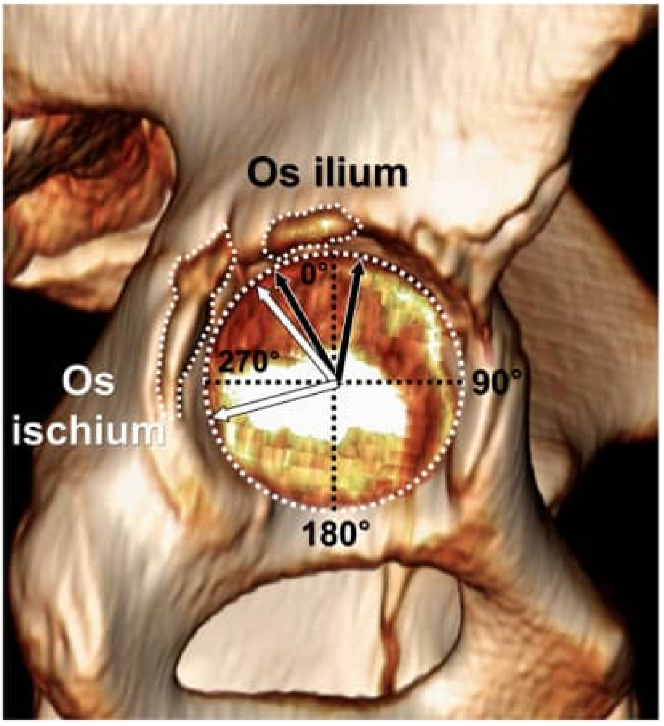

Fig. 3
The measurement technique to determine the locations of the secondary ossification centers of the acetabulum. An orientation using 0° for the superior acetabulum, 90° for the anterior acetabulum, 180° for the inferior acetabulum, and 270° for the posterior acetabulum was adopted. The black arrows indicate the starting and ending points of the os ilium, and the white arrows indicate the starting and ending points of the os ischium.

aspect was set at 270° for both the right and left hips. The starting and ending points of the secondary ossification centers were marked on the circle. These points and the arc angle between the starting and ending points were measured. The locations of the anterior and posterior flanges of the TRC were measured as a reference.

Acetabular Coverage Increase by the Secondary Ossification Centers

The amount of acetabular coverage increase by the acetabular secondary ossification centers was defined as the difference in each acetabular sector angle (ΔASA) measured with and without the acetabular secondary ossification center (Fig. 4)[10,11]. ΔASAs were evaluated in the following regions of the acetabulum: posterior (ΔPASA), posterosuperior (ΔPSASA), superior (ΔSASA), anterosuperior (ΔASASA), and anterior (ΔAASA)[10,11]. ΔSASA was measured on a reformatted coronal plane parallel to the anterior pelvic plane (APP) and passing through the center of the femoral head. Measurements were not made on a plane that connected the midpoint of the acetabular notch and the opposite point on a line through the center of the circle. The APP, defined as the plane formed by the bilateral anterosuperior iliac spines and the midpoint between the pubic tubercles, has commonly been used as a reference plane for the pelvis[10,12-14]. ΔPASA and ΔAASA were measured on an axial plane orthogonal to the APP and passing through the center of the femoral head. ΔPSASA and ΔASASA were measured on an oblique coronal plane passing through the center of the femoral head and were directed 45° posterior (ΔPSASA) or anterior (ΔASASA) relative to the APP. Previous studies have shown a correlation between the SASA on CT scans and the lateral center-edge angle on radiographs[15,16] or a significant difference in ASAs between patients with symptomatic hip dysplasia and asymptomatic controls[5].

Age-Related Differences in the Location of and Acetabular Coverage by the Secondary Ossification Centers

Patients were grouped into 3 age ranges: (1) late childhood (9 to 10 years of age for boys and 8 to 9 years for girls), (2)

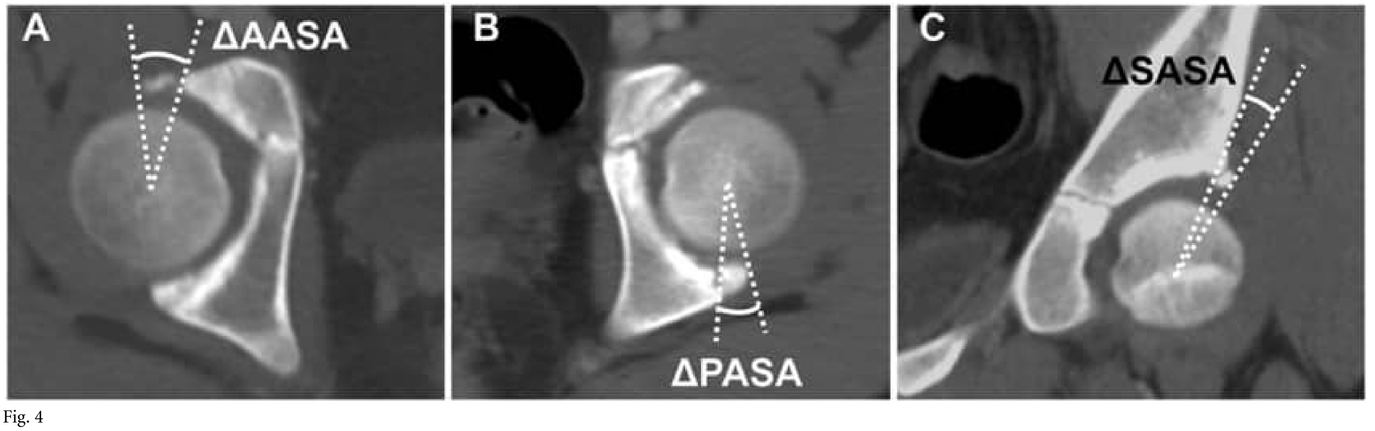

Fig. 4
The measurement technique for determining the amount of acetabular coverage increase by the secondary ossification centers of the acetabulum. **Fig. 4-A** ΔAASA was defined as the difference in the anterior acetabular sector angle measured with and without the os pubis on the axial plane orthogonal to the anterior pelvic plane and passing through the center of the femoral head. **Fig. 4-B** ΔPASA was defined as the difference in the posterior acetabular sector angle measured with and without the os ischium on the axial plane orthogonal to the anterior pelvic plane and passing through the center of the femoral head. **Fig. 4-C** ΔSASA was defined as the difference in the superior acetabular sector angle measured with and without the os ilium on the coronal plane parallel to an anterior pelvic plane and passing through the center of the femoral head.

TABLE II Intraclass Correlation Coefficients Calculated to Evaluate Intraobserver and Interobserver Reliabilities

Parameter	Intraobserver*	Interobserver*
Starting position of the os ischium	0.840 (0.780 to 0.881)	0.812 (0.729 to 0.866)
Ending position of the os ischium	0.812 (0.764 to 0.851)	0.725 (0.656 to 0.781)
Starting position of the os ilium	0.807 (0.730 to 0.864)	0.717 (0.609 to 0.798)
Ending position of the os ilium	0.910 (0.868 to 0.939)	0.865 (0.785 to 0.913)
Starting position of the os pubis	0.784 (0.717 to 0.837)	0.717 (0.633 to 0.784)
Ending position of the os pubis	0.788 (0.722 to 0.840)	0.704 (0.617 to 0.774)
Anterior flange of the TRC	0.767 (0.640 to 0.854)	0.747 (0.659 to 0.815)
Posterior flange of the TRC	0.808 (0.587 to 0.901)	0.704 (0.589 to 0.788)
ΔPASA	0.827 (0.753 to 0.880)	0.903 (0.878 to 0.923)
ΔPSASA	0.884 (0.311 to 0.965)	0.705 (0.512 to 0.821)
ΔSASA	0.963 (0.946 to 0.975)	0.842 (0.802 to 0.873)
ΔASASA	0.834 (0.513 to 0.941)	0.867 (0.444 to 0.968)
ΔAASA	0.837 (0.767 to 0.887)	0.832 (0.791 to 0.866)

*The values are given as the intraclass correlation coefficient, with the 95% CI in parentheses. Intraclass correlation coefficients for absolute agreement were calculated from a 2-way random effects model.

preadolescence (11 to 12 years for boys and 10 to 11 years for girls), and (3) early adolescence (13 to 14 years for boys and 12 to 13 years for girls). Male patients were grouped with younger female patients because the appearance and closure of the acetabular secondary ossification centers of female patients precede those of male patients by 1 to 2 years (Fig. 2)[2,9]. The locations of the secondary ossification centers and the amount of acetabular coverage increase by the acetabular secondary ossification centers were analyzed by age group.

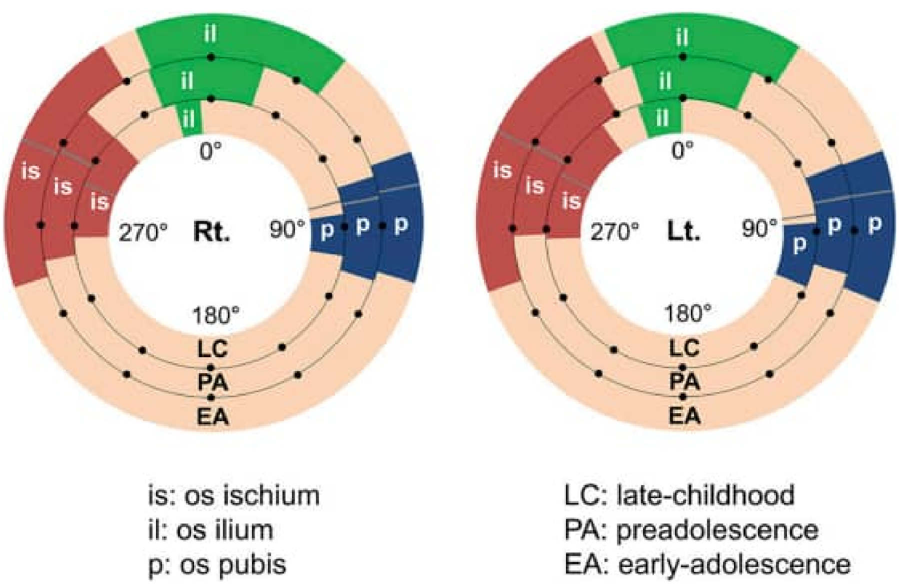

Fig. 5

The median starting and ending points of the secondary ossification centers of the acetabulum. On the right (Rt.) side, the median values were 269° to 316° for the os ischium, 345° to 356° for the os ilium, and 81° to 99° for the os pubis in late childhood; 259° to 313° for the os ischium, 338° to 18° for the os ilium, and 72° to 108° for the os pubis in preadolescence; and 252° to 328° for the os ischium, 338° to 39° for the os ilium, and 73° to 107° for the os pubis in early adolescence. On the left (Lt.) side, the median values were 268° to 324° for the os ischium, 341° to 0° for the os ilium, and 88° to 113° for the os pubis in late childhood; 267° to 330° for the os ischium, 342° to 24° for the os ilium, and 68° to 106° for the os pubis in preadolescence; and 251° to 333° for the os ischium, 337° to 33° for the os ilium, and 70° to 113° for the os pubis in early adolescence. The gray lines indicate the anterior and posterior flanges of the TRC.

TABLE III Locations of the Secondary Ossification Centers of the Acetabulum

Group	Laterality	Ossification Center	Position*		Arc Angle*	P Value (Effect Size)†		
			Starting	Ending		Versus Late Childhood	Versus Preadolescence	Versus Early Adolescence
Late childhood	Right	Os ischium (n = 19)	269 (263 to 273)	316 (306 to 323)	42 (37 to 55)	—	0.057 (0.200)	<0.001‡ (0.557)
		Os ilium (n = 4)	345 (342 to 348)	356 (355 to 362)	14 (10 to 21)	—	0.013‡ (0.446)	0.005‡ (0.516)
		Os pubis (n = 16)	81 (73 to 86)	99 (94 to 107)	17 (8 to 34)	—	0.010‡ (0.268)	0.049‡ (0.314)
	Left	Os ischium (n = 19)	268 (263 to 280)	324 (308 to 330)	52 (34 to 57)	—	0.009‡ (0.249)	<0.001‡ (0.604)
		Os ilium (n = 4)	341 (338 to 344)	0 (354 to 8)	15 (13 to 23)	—	0.039‡ (0.332)	0.001‡ (0.540)
		Os pubis (n = 16)	88 (74 to 93)	113 (105 to 124)	26 (19 to 37)	—	0.036‡ (0.267)	0.037‡ (0.361)
Preadolescence	Right	Os ischium (n = 72)	259 (248 to 267)	313 (301 to 327)	54 (41 to 75)	0.057 (0.200)	—	<0.001‡ (0.323)
		Os ilium (n = 25)	338 (324 to 344)	18 (5 to 30)	44 (24 to 59)	0.013‡ (0.446)	—	0.016‡ (0.308)
		Os pubis (n = 49)	72 (56 to 80)	108 (100 to 124)	36 (20 to 67)	0.010‡ (0.268)	—	0.815 (0.024)
	Left	Os ischium (n = 70)	267 (253 to 277)	330 (316 to 336)	61 (46 to 76)	0.009‡ (0.249)	—	0.001‡ (0.367)
		Os ilium (n = 27)	342 (330 to 350)	24 (15 to 33)	42 (29 to 56)	0.039‡ (0.332)	—	0.016‡ (0.355)
		Os pubis (n = 47)	68 (52 to 76)	106 (98 to 116)	37 (27 to 56)	0.036‡ (0.267)	—	0.464 (0.089)
Early adolescence	Right	Os ischium (n = 32)	252 (237 to 261)	328 (315 to 340)	79 (58 to 93)	<0.001‡ (0.557)	<0.001‡ (0.323)	—
		Os ilium (n = 22)	338 (328 to 338)	39 (22 to 54)	63 (41 to 79)	0.005‡ (0.516)	0.013‡ (0.308)	—
		Os pubis (n = 17)	73 (52 to 80)	107 (100 to 128)	35 (21 to 76)	0.049‡ (0.314)	0.815 (0.024)	—
	Left	Os ischium (n = 31)	251 (233 to 268)	333 (319 to 341)	88 (69 to 104)	<0.001‡ (0.604)	0.001‡ (0.367)	—
		Os ilium (n = 25)	337 (328 to 345)	33 (26 to 43)	57 (48 to 70)	0.001‡ (0.540)	0.016‡ (0.355)	—
		Os pubis (n = 18)	70 (60 to 78)	113 (110 to 124)	43 (33 to 61)	0.037‡ (0.361)	0.464 (0.089)	—

*The values are given as the median value, with the interquartile range in parentheses, in degrees. †P values comparing the arc angles of the secondary ossification centers between age groups were calculated using the Wilcoxon rank sum test. Effect sizes were calculated by dividing the absolute standardized test statistic, z, by the square root of the number of pairs. ‡Significant.

Statistical Analysis

The frequency of each secondary ossification center was compared between male and female patients using the Fisher exact test, and corresponding patient ages were compared between male and female patients using the Student t test. The Wilcoxon signed-rank test was used to compare the ASAs measured with and without each secondary ossification center. The arc angles from the starting point to the ending point of the secondary ossification centers and ΔASAs were compared between the age groups, between the right and left hips, and between male and female patients using the Wilcoxon rank sum test.

Reliability tests were performed on 50 randomly selected acetabular samples. To determine the intraobserver reliability, measurements were made by the first author (Y.J.C.) twice, 4 weeks apart. To determine the interobserver reliability, the same measurements were made by another author (Y.M.C.) after a consensus-building session to define the radiographic measurements. The intraobserver and interobserver reliabilities of the measurements were evaluated using the intraclass correlation coefficient (Table II).

Significance was set at $p < 0.05$. Statistical analyses were performed using R 4.2.2 (The R Foundation).

Results

Locations of Acetabular Secondary Ossification Centers

The median starting and ending points and arc angles of the os ischium, os ilium, and os pubis are shown in Figure 5 and Table III. Compared with the late-childhood group, the early-adolescence group tended to have wider arc angles of the os ischium ($p < 0.001$ for both sides), os ilium ($p = 0.005$ for the right side and $p = 0.001$ for the left side), and os pubis ($p = 0.049$ for the right side and $p = 0.037$ for the left side).

There were no significant differences between the right and left hips for the median arc angles of the os ischium ($p = 0.239$), os ilium ($p = 0.933$), and os pubis ($p = 0.335$) (see Appendix Supplementary Table II) or between male and female patients for the median arc angles of the right os ischium ($p = 0.457$), os ilium ($p = 0.426$), and os pubis ($p = 0.892$) and the left os ischium ($p = 0.311$), os ilium ($p = 0.305$), and os pubis ($p = 0.800$) (see Appendix Supplementary Table III).

Acetabular Coverage Increase by Secondary Ossification Centers

The frequency of the secondary ossification center in each area of the acetabulum by age, sex, and laterality is shown in Appendix Supplementary Table IV.

Overall, the median ASAs measured with the secondary ossification center were larger than those measured without it in every area of the acetabulum evaluated. On the right side, ΔPASA = 9.9° (95% confidence interval [CI], 9.2° to 11.0°; $p < 0.001$), ΔPSASA = 11.4° (95% CI, 10.4° to 12.9°; $p < 0.001$), ΔSASA = 9.5° (95% CI, 6.7° to 11.5°; $p < 0.001$), ΔASASA = 9.3° (95% CI, 7.0° to 11.4°; $p < 0.001$), and ΔAASA = 4.1° (95% CI, 3.0° to 5.4°; $p < 0.001$). On the left side, ΔPASA = 8.9° (95% CI, 8.1° to 9.6°; $p < 0.001$),

TABLE IV Increases in Acetabular Coverage by the Secondary Ossification Centers of the Acetabulum*

				P Value (Effect Size)‡		
Group	Laterality	ΔASA	Value† *(deg)*	Versus Late Childhood	Versus Preadolescence	Versus Early Adolescence
Late childhood	Right	ΔPASA (n = 16)	8.1 (5.9 to 9.8)	—	0.010§ (0.296)	0.026§ (0.365)
		ΔPSASA (n = 8)	14.0 (8.0 to 15.3)	—	0.522 (0.083)	0.832 (0.040)
		ΔSASA (n = 2)	9.9 (9.7 to 10.0)	—	1.000 (0.000)	0.857 (0.146)
		ΔASASA (n = 2)	11.1 (10.3 to 11.9)	—	0.529 (0.181)	0.273 (0.372)
		ΔAASA (n = 4)	3.9 (3.0 to 4.3)	—	0.816 (0.055)	0.061 (0.566)
	Left	ΔPASA (n = 17)	7.0 (6.0 to 8.9)	—	0.072 (0.212)	0.034§ (0.351)
		ΔPSASA (n = 7)	6.9 (4.8 to 9.4)	—	0.048§ (0.253)	0.018§ (0.404)
		ΔSASA (n = 2)	5.8 (5.6 to 5.9)	—	0.198 (0.390)	0.286 (0.471)
		ΔASASA (n = 0)	NA	—	NA	NA
		ΔAASA (n = 2)	5.4 (3.9 to 6.9)	—	0.458 (0.171)	1.000 (0.000)
Preadolescence	Right	ΔPASA (n = 59)	10.1 (7.7 to 12.8)	0.010§ (0.365)	—	0.500 (0.076)
		ΔPSASA (n = 54)	11.1 (7.7 to 13.4)	0.522 (0.083)	—	0.085 (0.192)
		ΔSASA (n = 8)	9.2 (4.8 to 12.0)	1.000 (0.000)	—	0.724 (0.122)
		ΔASASA (n = 15)	10.1 (8.3 to 11.6)	0.529 (0.181)	—	0.261 (0.233)
		ΔAASA (n = 20)	3.8 (0.9 to 5.7)	0.816 (0.055)	—	0.104 (0.312)
	Left	ΔPASA (n = 56)	9.3 (6.7 to 10.7)	0.072 (0.212)	—	0.184 (0.153)
		ΔPSASA (n = 55)	10.7 (7.9 to 13.3)	0.048§ (0.253)	—	0.059 (0.208)
		ΔSASA (n = 12)	11.4 (9.1 to 13.5)	0.198 (0.390)	—	1.000 (0.000)
		ΔASASA (n = 15)	11.9 (7.4 to 13.6)	NA	—	0.285 (0.222)
		ΔAASA (n = 20)	3.3 (2.0 to 4.6)	0.458 (0.171)	—	0.195 (0.250)
Early adolescence	Right	ΔPASA (n = 22)	10.7 (7.6 to 17.4)	0.026§ (0.296)	0.500 (0.076)	—
		ΔPSASA (n = 27)	12.9 (10.2 to 14.7)	0.833 (0.040)	0.085 (0.192)	—
		ΔSASA (n = 5)	8.4 (8.0 to 12.3)	0.857 (0.146)	0.724 (0.122)	—
		ΔASASA (n = 10)	7.4 (5.5 to 9.5)	0.273 (0.372)	0.261 (0.233)	—
		ΔAASA (n = 8)	5.6 (4.4 to 6.5)	0.061 (0.566)	0.104 (0.312)	—
	Left	ΔPASA (n = 20)	9.9 (7.3 to 13.7)	0.034§ (0.351)	0.184 (0.153)	—
		ΔPSASA (n = 28)	11.7 (10.3 to 15.8)	0.018§ (0.404)	0.059 (0.208)	—
		ΔSASA (n = 6)	10.9 (8.3 to 14.4)	0.286 (0.471)	1.000 (0.000)	—
		ΔASASA (n = 10)	8.6 (6.8 to 11.7)	NA	0.285 (0.222)	—
		ΔAASA (n = 8)	4.6 (3.4 to 5.3)	1.000 (0.000)	0.195 (0.250)	—

*NA = not applicable. †The values are given as the median, with the interquartile range in parentheses. ‡P values comparing the amount of acetabular coverage increase by each secondary ossification center between the age groups were calculated using the Wilcoxon rank sum test. Effect sizes were calculated by dividing the absolute standardized test statistic, z, by the square root of the number of pairs. §Significant.

ΔPSASA = 10.9° (95% CI, 9.9° to 11.9°; $p < 0.001$), ΔSASA = 10.6° (95% CI, 8.4° to 12.8°; $p < 0.001$), ΔASASA = 9.8° (95% CI, 7.7° to 13.2°; $p < 0.001$), and ΔAASA = 3.7° (95% CI, 2.9° to 5.2°; $p < 0.001$).

There was no difference between the late-childhood and early-adolescence groups with regard to the median ΔSASA (right: p = 0.857, and left: p = 0.286) and ΔAASA (right: 0.061, and left: p = 1.000). However, the median ΔPASA in the right hips (p = 0.026) and the median ΔPASA (p = 0.034) and ΔPSASA (p = 0.018) in the left hips were larger in the early-adolescence group than in the late-childhood group (Table IV; see also Appendix Figs. S1 and S2).

Between the right and left hips, the median values did not differ for ΔPASA (p = 0.046), ΔPSASA (p = 0.324), ΔSASA (p = 0.386), ΔASASA (p = 0.355), and ΔAASA (p = 0.751). The median ΔPASA (right: p = 0.489; left: p = 0.354), ΔPSASA (right: p = 0.759; left: p = 0.680), ΔSASA (right: p = 0.867; left: p = 0.238), ΔASASA (right: p = 0.596; left: p = 0.598), and ΔAASA (right: p = 0.266; left: p = 0.506) did not differ between males and females (see Appendix Supplementary Table V).

Discussion

To our knowledge, this is the first study to investigate the locations of the acetabular secondary ossification centers, the corresponding changes in acetabular coverage, and their age-related differences. Knowledge of the development of these centers may aid in better predicting and improving the prognosis of pediatric patients with hip instability or FAI. Moreover, it will help to achieve better radiographic identification of acetabular fractures. Our findings could guide future imaging studies of both the acetabular bone and cartilage.

In the current study, the os ischium formed near the posterior flange of the TRC and the os pubis formed slightly inferior to the anterior flange of the TRC in the late-childhood group, and both ossification centers were observed to span more extended areas in the superior and inferior directions along the acetabular rim in older age groups (Fig. 5). Ponseti reported that the os pubis, named the "os acetabuli" in his postmortem study, existed in the acetabular cartilage near the pubis in a 9-year-old girl, and the os ischium existed in the superior central part of the acetabular cartilage near the ischium in a 14-year-old boy[1]. Unfortunately, he did not describe the exact locations of the os pubis and os ischium; thus, we were unable to make a comparison with our results. However, he reported that the superior part of the os pubis extended superiorly into the anterior flange of the TRC in both children, which supports our data. If Ponseti had observed more adolescents, he might have found extension of the os pubis in both the superior and inferior directions, as in our results. In the current study, the os ilium formed near the midpoint between the anterior and posterior margins of the acetabulum in late childhood and covered more extended areas in older age groups (Fig. 5). Because all 3 secondary ossification centers extended along the acetabular rim, narrowing the gaps between them, we expect these ossification centers to eventually fuse, resulting in a smooth osseous rim of the acetabulum.

In the superior area of the acetabulum, the median increase in acetabular coverage by the os ilium was 5.8° to 11.4° in our study, whereas Morris et al. reported that the lateral center-edge angle increased by a mean of 4.1° from before the appearance to after fusion of the posterior rim of the acetabulum[8]. The difference in the increase in acetabular coverage by a secondary ossification center between the 2 studies may be attributed to the differences in the imaging modality (CT scans compared with radiographs), type and definition of the secondary ossification center (os ilium compared with the posterior rim of the acetabulum), and radiographic parameter (SASA compared with lateral center-edge angle).

In the current study, ΔPASA was larger in the early-adolescence group than in the late-childhood group, whereas ΔAASA, ΔASASA, and ΔSASA did not differ between the age groups. Hingsammer et al. reported that the PASA was larger in their older age group (15 ± 2 years) than in their younger age group (11 ± 2 years), whereas AASA was not[11]. The larger ΔPASA in the older age group observed in our study may contribute to the larger PASA in the older age group, resulting in increased acetabular anteversion with skeletal maturity.

The frequency of the acetabular secondary ossification centers by age has previously been reported in only a single study[2]. Its authors reported the highest frequency of the secondary ossification centers in boys 11.5 to 12.4 years of age and in girls 10.5 to 11.4 years of age, which agrees with our data (Fig. 2; see also Appendix Supplementary Table IV). However, their frequency of os ischium (boys: 0% to 67%; girls: 0% to 38%), os ilium (boys: 0% to 50%; girls: 0% to 43%), and os pubis (boys: 0% to 67%; girls: 0% to 29%) by age were higher than ours. This may be because we included only patients with distinct secondary ossification centers that could be differentiated from the acetabulum and from each other to measure the precise location of and acetabular coverage by each ossification center. It may be also attributed to the difference in the selected CT planes: they reported the frequency of the secondary ossification centers using every CT plane, whereas we investigated the frequency in 5 specific planes (see Appendix Supplementary Table IV).

This study had some limitations. First, we used a cross-sectional design, which is less suitable than longitudinal studies for investigating development. However, because it is unethical to repeat CT scans merely for research, we had no choice but to compare the parameters between different age groups. Second, the small number of patients in some subgroups might have led to underpowered results. Third, the development of the acetabular secondary ossification centers in pathologic hips, such as those with developmental dysplasia of the hip, might differ from that in normal hips. Because we included only hips that were expected to have normal development, our results might not be generalizable to pathologic hips. Fourth, chronological age was used instead of bone age in our study, as hip radiographs for bone age assessment were not available in every patient[17]. Fifth, the CT scan slice thickness in the current study was relatively thick at 3 to 5 mm, which may have resulted in the exclusion of patients with small ossification centers. Lastly, we did not evaluate ΔASAs based on cartilage, which may differ from ΔASAs based on bone.

In conclusion, this study indicated that, during early adolescence, the secondary ossification centers span more extended areas along the acetabular rim than during late childhood. This leads to a reduction in the gaps between the ossification centers. Each secondary ossification center of the acetabulum increases acetabular coverage of the femoral head. However, in early adolescence, the increment in acetabular coverage by the secondary ossification centers tended to be larger in the posterior area but not in the anterior or superior area than during late childhood.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/I126). ■

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References

1. Ponseti IV. Growth and development of the acetabulum in the normal child. Anatomical, histological, and roentgenographic studies. J Bone Joint Surg Am. 1978 Jul;60(5):575-85.

2. Parvaresh KC, Pennock AT, Bomar JD, Wenger DR, Upasani VV. Analysis of acetabular ossification from the triradiate cartilage and secondary centers. J Pediatr Orthop. 2018 Mar;38(3):e145-50.

3. Peterson JB, Doan J, Bomar JD, Wenger DR, Pennock AT, Upasani VV. Sex differences in cartilage topography and orientation of the developing acetabulum: implications for hip preservation surgery. Clin Orthop Relat Res. 2015 Aug;473(8):2489-94.

4. Portinaro NM, Murray DW, Benson MK. Microanatomy of the acetabular cavity and its relation to growth. J Bone Joint Surg Br. 2001 Apr;83(3):377-83.

5. Verhaegen JCF, DeVries Z, Horton I, Slullitel PA, Rakhra K, Beaulé PE, Grammatopoulos G. Acetabular sector angles in asymptomatic and dysplastic hips: defining dysplasia and thresholds to guide management. J Bone Joint Surg Am. 2023 Nov 1;105(21):1709-20.

6. Nepple JJ, Wells J, Ross JR, Bedi A, Schoenecker PL, Clohisy JC. Three patterns of acetabular deficiency are common in young adult patients with acetabular dysplasia. Clin Orthop Relat Res. 2017 Apr;475(4):1037-44.

7. Knipe H, Weerakkody Y, Niknejad M. Os acetabuli. 2022. Accessed 2023 Feb 22. https://radiopaedia.org/articles/27959.

8. Morris WZ, Chen JY, Cooperman DR, Liu RW. Characterization of ossification of the posterior rim of acetabulum in the developing hip and its impact on the assessment of femoroacetabular impingement. J Bone Joint Surg Am. 2015 Feb 4;97(3):e11.

9. Kim SH, Yoon HK, Han H, Cho SW, Seo YK. Ossification of the triradiate cartilage and posterior acetabulum. J Korean Soc Radiol. 2019;80(3):503-12.

10. Fujii M, Nakashima Y, Yamamoto T, Mawatari T, Motomura G, Matsushita A, Matsuda S, Jingushi S, Iwamoto Y. Acetabular retroversion in developmental dysplasia of the hip. J Bone Joint Surg Am. 2010 Apr;92(4):895-903.

11. Hingsammer AM, Bixby S, Zurakowski D, Yen YM, Kim YJ. How do acetabular version and femoral head coverage change with skeletal maturity? Clin Orthop Relat Res. 2015 Apr;473(4):1224-33.

12. Imai N, Ito T, Takahashi Y, Horigome Y, Suda K, Miyasaka D, Minato I, Endo N. In vivo relationship between the clinical epicondylar axis and the anterior pelvic plane in normal subjects. J Biomed Sci Eng. 2013;6:863-8.

13. Perreira AC, Hunter JC, Laird T, Jamali AA. Multilevel measurement of acetabular version using 3-D CT-generated models: implications for hip preservation surgery. Clin Orthop Relat Res. 2011 Feb;469(2):552-61.

14. Lewinnek GE, Lewis JL, Tarr R, Compere CL, Zimmerman JR. Dislocations after total hip-replacement arthroplasties. J Bone Joint Surg Am. 1978 Mar;60(2):217-20.

15. Monazzam S, Bomar JD, Cidambi K, Kruk P, Hosalkar H. Lateral center-edge angle on conventional radiography and computed tomography. Clin Orthop Relat Res. 2013 Jul;471(7):2233-7.

16. Ito H, Matsuno T, Hirayama T, Tanino H, Yamanaka Y, Minami A. Three-dimensional computed tomography analysis of non-osteoarthritic adult acetabular dysplasia. Skeletal Radiol. 2009 Feb;38(2):131-9.

17. Furdock RJ, Benedick AJ, Nelson G, Li D, Cooperman DR, Sanders JO, Liu RW. Systematic isolation of key parameters for estimating skeletal maturity on AP hip radiographs. J Pediatr Orthop. 2021 Sep 1;41(8):483-9.