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ORIGINAL ARTICLE

Can the proximal humeral ossification system (PHOS) effectively guide brace weaning in patients with adolescent idiopathic scoliosis?

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Abstract

Purpose The proximal humeral epiphyses can be conveniently viewed in routine spine radiographs. This study aimed to investigate whether the proximal humeral epiphyseal ossification system (PHOS) can be used to determine the timing of brace weaning in adolescent idiopathic scoliosis (AIS), as assessed by the rate of curve progression after brace weaning.
Methods A total of 107 patients with AIS who had weaned brace-wear at Risser Stage ≥ 4, no bodily growth and post-menarche ≥ 2 years between 7/2014 and 2/2016 were studied. Increase in major curve Cobb angle > 5° between weaning and 2-year follow-up was considered curve progression. Skeletal maturity was assessed using the PHOS, distal radius and ulna (DRU) classification, Risser and Sanders staging. Curve progression rate per maturity grading at weaning was examined.
Results After brace-wear weaning, 12.1% of the patients experienced curve progression. Curve progression rate for weaning at PHOS Stage 5 was 0% for curves < 40°, and 20.0% for curves ≥ 40°. No curve progression occurred when weaning at PHOS Stage 5 with radius grade of 10 for curves ≥ 40°. Factors associated with curve progression were: Months post-menarche ($p = 0.021$), weaning Cobb angle ($p = 0.002$), curves < 40° versus ≥ 40° ($p = 0.009$), radius ($p = 0.006$) and ulna ($p = 0.025$) grades, and Sanders stages ($p = 0.025$), but not PHOS stages ($p = 0.454$).
Conclusion PHOS can be a useful maturity indicator for brace-wear weaning in AIS, with PHOS Stage 5 having no post-weaning curve progression in curves < 40°. For large curves ≥ 40°, PHOS Stage 5 is also effective in indicating the timing of weaning together with radius grade ≥ 10.

Keywords Proximal humerus ossification system · PHOS · Skeletal maturity · Curve progression · Adolescent idiopathic scoliosis

Introduction

For patients with adolescent idiopathic scoliosis (AIS), growth potential and curve magnitude are key components influencing curve progression risk [1, 2]. Skeletal bone age is an important measure in determining the remaining growth potential during puberty [3, 4], and it is one of the major factors for clinical decision making [5]. The timing of peak growth and growth cessation are crucial for the introduction of an intervention, such as bracing, as well as its discontinuation. Precise assessment of skeletal maturity can ensure timely treatment [6–8], but also minimize prolonged bracing which can have detrimental effects on patients' health-related quality of life [9], and potential muscle weakness and osteoporosis [10].

Despite its simplicity and popular use worldwide, Risser staging is found as an inaccurate [11] and inadequate maturity measure which can underestimate the skeletal maturity of patients with AIS [12], leading to prolonged bracing [13]. Hence, increased demand on more accurate skeletal maturity assessments led to the popularity of hand and wrist bone age assessments such as Sanders staging [14] and the Distal Radius and Ulna (DRU) classification [15–17]. However, this entails an additional hand-wrist radiograph for assessment. Recent development of the proximal humeral epiphyseal ossification system (PHOS) has peaked interest since it has demonstrated good reliability and prediction of the peak

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height velocity (PHV) and is visualized on the same spine radiograph [18–20] for scoliotic curve assessment.

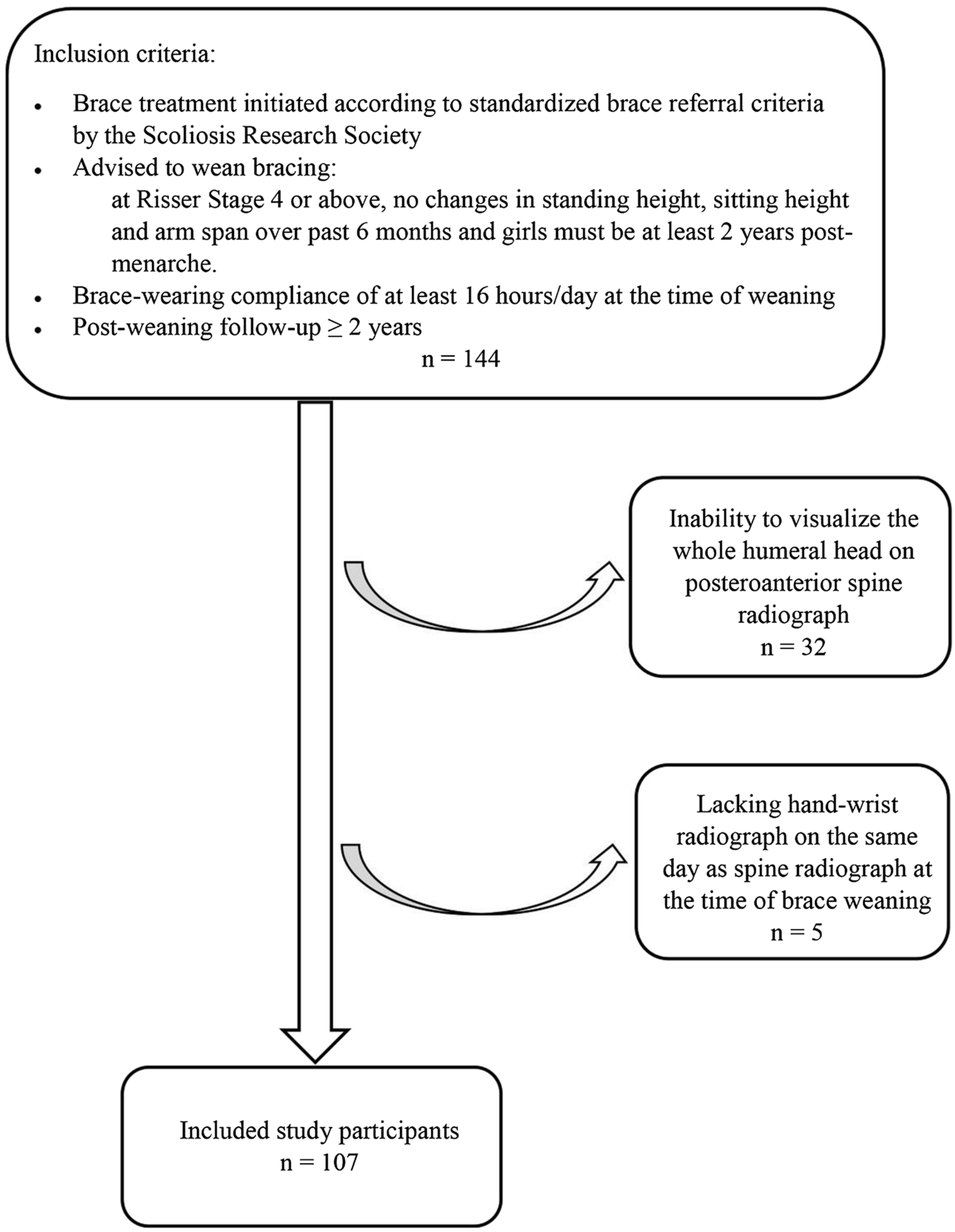
There is a clear advantage of limiting radiation exposure by avoiding additional hand-wrist radiographs if the PHOS can determine growth cessation and thus appropriate timing of brace weaning. Previous studies only demonstrated correlation of the PHOS with the PHV and the remaining growth potential [18, 19] but not with treatment outcome. This study aims henceforth: (1) to investigate whether the timing of brace weaning can be determined by the PHOS, as assessed by the rate of *curve progression* after brace weaning, (2) to assess how the stages of the PHOS relate to other commonly used skeletal maturity indices at the time of weaning. We hypothesize that the PHOS stages are associated with the occurrence of curve progression after brace weaning in AIS, and thus it can be an appropriate indicator for initiating brace weaning.

Methods

Study design

This was a retrospective assessment of patients with AIS who underwent brace weaning during the period of July 2014 to February 2016 (Fig. 1). All patients underwent brace treatment according to a standardized brace referral criteria as suggested by the Scoliosis Research Society [21]: age

Fig. 1 Flowchart of patient recruitment



between 10 and 14 years at initial presentation, major curve magnitude of 25° to 40°, less than 1 year post-menarche, Risser Stages 0 to 2, and no history of prior treatment. They were advised to wear the prescribed brace full-time for 20 h per day, comparable to the 20 to 24 h per day stated in the SOSORT management guidelines [22]. Patients were included when they were advised to wean bracing at Risser Stage 4 or above, no changes of standing height, sitting height and arm span for the past six months, and girls must be at least 2 years post-menarche. These patients must have a brace-wearing compliance of at least 16 h per day at the time of weaning, as monitored with the aid of thermal sensors. At the time of weaning, the attending specialist then instructed the patient to either gradually wean bracing through nocturnal wear for six months prior to complete brace removal, or to immediately stop the brace-wear. Each patient included in this study must have a post-weaning follow-up of 2 years or more. This study had ethics approval from the local ethics committee, and parents' informed consent were obtained.

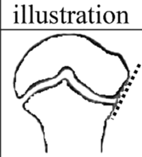
Data collection and outcome measures

Patients' demographic information including sex, chronological age at the time of weaning, date of onset of menarche (for girls) and bodily growth parameters (standing body height, sitting height and arm span) were recorded. Their radiographical skeletal maturity parameters, curve type (according to major curve based on the apex—major thoracic or major lumbar), and major curve Cobb angle [23] were measured by attending surgeons without prior knowledge of this study. The time of weaning was considered as baseline. The weaning protocol of nocturnal bracing for 6 months or immediate discontinuation of brace-wear was also recorded. Any increase in major curve Cobb angle > 5° between baseline and the final follow-up visit at 2 years after weaning was considered curve progression. All baseline spine radiographs were taken with patients being out of brace for 24 h.

Skeletal maturity parameters

Skeletal maturity at baseline was assessed using the US Risser staging [24, 25] with Stages 4, 4 + or 5. Stage 4 + referred to capping of the iliac crest apophysis prior to complete fusion at Stage 5. This has been used by our spine surgeons in daily clinical practice to further segregate patients who were between Risser Stage 4 and 5, as Risser Stage 4 was found least effective in indicating the beginning of growth plateau [12], yet having reached Stage 5 failed to indicate how long the apophysis had been fused. Risser Stage 4 + in the US system is equivalent to the European Risser Stage 4 which represents the beginning of fusion of the apophysis to the ilium posteromedially [26]. The periphyseal changes of the humeral head was also examined for the maturity of the patients at weaning using the PHOS [18], which consists of Stage 1 to 5 with increasing maturity, with Stage 3 to 5 focusing on the lateral half of the physis from open (Stage 3) to partial (Stage 4) until complete fusion (Stage 5) (Fig. 2). Only Stages 3 to 5 were observed for the entire cohort of patients studied. Bone age was assessed using Sanders staging [27] ranging from Stages 1 to 8 (referred as SS1 to SS8). SS7 represented early mature state with all phalangeal physes completely fused except the distal radial and ulnar physes, with subclassification SS7a depicting the medial physeal plate of the distal ulna exhibiting narrowing or some extent of fusion (≤ 50%) at the medial side, and SS7b referred to greater than 50% fusion of the medial growth plate [28]. SS8 was graded when the distal radial physis was completely closed in addition to all the fused phalangeal physes. From the hand-wrist radiograph, the DRU classification [15] was assessed ranging from radius grade (R) 1 to 11 and ulna (U) grade 1 to 9. R9 represented the blurred central physis of the distal radius whereas R10 represented a completely

Fig. 2 The proximal humerus ossification system (PHOS) with Stage 3 to 5 focusing on the lateral half of the physis from open to close

PHOS Stage	Schematic illustration	Radiographic characteristics of the proximal humerus
3		The lateral half of the physis is open without obvious fusion - the lateral margin of the epiphysis is as wide as the metaphysis
4		The lateral half of the physis thins and begins partial fusion
5		Complete fusion of the lateral half of the physis.

obliterated physeal line with notches at both medial and lateral ends of the growth plate. Both R11 and U9 were the final grades representing full skeletal maturity and complete fusion of the physes.

Statistical analysis

Descriptive statistics were presented in mean values with standard deviation (SD) and frequencies in percentages. Shapiro–Wilk tests were performed to assess the normality of data. The relationship of the PHOS with other skeletal maturity indices at the time of weaning were investigated using Goodman and Kruskal's gamma with Bonferroni correction, whose coefficient (G) ranges from − 1 (perfect inverse correlation) to + 1 (perfect positive correlation) [29]. Patients were stratified into curve progression and non-progression groups according to the changes of Cobb angle at post-weaning 2 years. Curve magnitude at the time of weaning was evaluated for any intergroup difference for each skeletal maturity grading at weaning by the Mann–Whitney U test. Curve progression rates (in percentages) were observed in relation to the curve magnitude at weaning (< 30° versus ≥ 30° and < 40° versus ≥ 40°) per grading of each skeletal maturity index. The 30° threshold was examined as major curves < 30° at skeletal maturity was found unlikely to progress [30], whereas the 40° threshold was also used for analysis as it represents the cut-off for adult deterioration risk [31]. Through the use of point-biserial correlation test and maximum likelihood ratio Chi-square test with Bonferroni correction, independent parameters including age, sex, months post-menarche, curve magnitude and the skeletal maturity grading at weaning were tested for any associations with whether the curve progressed (dichotomized into yes/no) after brace weaning. Two raters without knowledge of the clinical data and other maturity parameters performed measurements of the PHOS independently. Inter-rater reliability was reported in weighted kappa with confidence interval (CI). Kappa values below 0.4 represent poor agreement, whereas values between 0.40 and 0.75 indicate fair to good agreement, and those ≥ 0.75 represent excellent agreement [32]. Excellent inter-rater reliability for the use of the PHOS was found with a weighted kappa of 0.84 (95% CI 0.75–0.93).

All statistical analyses were performed using SPSS Windows 27.0 (IBM SPSS Inc., Chicago, Illinois). A statistical significance was set at a level of p value of < 0.05.

Results

A total of 144 patients were identified, with 37 patients excluded as indicated by the following exclusion criteria: inability to visualize the whole humeral head on the posteroanterior spine radiograph (32 patients), and no hand-wrist radiographs at the time of brace weaning (5 patients). There were 107 patients (87.9% females) included for analysis. Their profile and characteristics at baseline (i.e. the time of weaning) are presented in Table 1. There was 31.8% (34/107) of the patients underwent gradual weaning. The weaning protocol (gradual/immediate) was not correlated to the changes of Cobb angle ($p = 0.610$) nor associated with whether there was curve progression ($p = 0.545$). The changes of Cobb angle were comparable between gradual and immediate weaning patients (2.4 ± 2.2° versus 2.8 ± 3.2° respectively, $p = 0.787$). At the time of weaning, the mean major curve Cobb angle was 35.6° (SD 7.4°) with 32.7% (35/107) of patients weaned bracing at ≥ 40°. The mean duration of post-brace weaning follow-up was 3.4 years (SD 1.8). The most prevalent grades at weaning for each skeletal maturity index were: Risser Stage 4 +, R10, U8, PHOS Stage 4, and SS8 (Table 1). PHOS stages were found correlated specifically to radius grades of the DRU classification (G: 0.32, $p = 0.025$), with PHOS Stage 5 being comprised of 3.3% R8 (n = 1), 30.0% R9 (n = 9), 33.3% R10 (n = 10) and 33.3% R11 (n = 10) (Table 1).

After brace weaning, 12.1% of the patients (13/107) experienced curve progression. Patients who experienced curve progression had larger curve magnitude at the time of weaning than those without curve progression ($p = 0.004$), with a mean Cobb angle increase of 7.6° (SD 2.2°) (Table 2). For patients who weaned brace-wear at PHOS Stage 4, Cobb angle at weaning was larger for those with post-weaning curve progression as compared to those without ($p = 0.007$). The same also occurred for patients who weaned bracing at Risser Stage 4 +, R9, U8, and SS7b (all at $p < 0.05$). Among patients weaning brace-wear at the same skeletal maturity status, all patients having Cobb angle < 30° (26.2% of the study cohort) at weaning did not progress (Table 3). Weaning Cobb angle ≥ 40° had higher curve progression rates than < 40°, with the exception of those who weaned at Risser Stage 4 with curve progression rate of 18.2% for < 40° versus 11.1% for ≥40° curves. The rate of curve progression for weaning at PHOS Stage 5 was 0.0% for curves < 40° versus 20.0% for those patients who weaned brace-wear at ≥ 40° (Table 3). Additional use of radius grade 10 was important for predicting curve progression risk when utilizing the PHOS. Crosstabulation revealed that for the < 40° group, no cases (0/35) experienced curve progression when weaned at PHOS Stage ≥ 4 and ≥ R10 (Fig. 3). As for curves ≥ 40°, no curve progression was also noted for weaning at PHOS Stage 5 and ≥ R10. The following parameters were each identified as significant factors associated with post-weaning curve progression: Number of months post-menarche ($p = 0.021$), Cobb angle at brace weaning ($p = 0.002$), curve magnitude <40° versus ≥ 40° ($p = 0.009$),

Table 1 Patient profile at the time of weaning (baseline)

Parameters mean (SD)/count in number (%)	Whole study population (n = 107)	Females (n = 94)	Males (n = 13)
Age (years)	14.7 (1.1)	14.6 (1.0)	15.9 (0.9)
Body height (cm)	160.4 (6.2)	159.6 (5.5)	167.1 (7.1)
Sitting height (cm)	85.2 (4.4)	85.0 (4.4)	88.8 (2.5)
Arm span (cm)	160.6 (7.3)	159.5 (6.3)	169.1 (8.3)
Number of months postmenarche at weaning		27.2 (9.1)	
Cobb angle of major curve (degrees)	35.6 (7.4)		
Number of large curves (Cobb angle of major curves ≥ 40°)	35 (32.7%)		
Curve type			
Thoracic	60 (56.1)		
Lumbar	47 (43.9)		

Skeletal maturity at baseline—count (% in columns)		Crosstabulation PHOS stages			
		3	4	5	*G* ^
Risser staging					
4	31 (29.0)	7 (35.0)	16 (28.1)	8 (26.7)	0.24
4+	62 (57.9)	13 (65.0)	34 (59.6)	15 (50.0)	
5	14 (13.1)	0	7 (12.3)	7 (23.3)	
DRU classification radius grade					
8	1 (0.9)	0	0	1 (3.3)	0.32*
9	43 (40.2)	11 (55.0)	23 (40.4)	9 (30.0)	
10	47 (43.9)	8 (40.0)	29 (50.9)	10 (33.3)	
11	16 (15.0)	1 (5.0)	5 (8.8)	10 (33.3)	
Ulna grade					
7	22 (20.6)	3 (15.0)	12 (21.1)	7 (23.3)	0.14
8	65 (60.7)	16 (80.0)	35 (61.4)	14 (46.7)	
9	20 (18.7)	1 (5.0)	10 (17.5)	9 (30.0)	
Sanders staging					
7a	22 (20.6)	3 (15.0)	12 (21.1)	7 (23.3)	0.11
7b	27 (25.2)	9 (45.0)	13 (22.8)	5 (16.7)	
8	58 (54.2)	8 (40.0)	32 (56.1)	18 (60.0)	
Proximal humeral ossification system (PHOS)					
3	20 (18.7)				
4	57 (53.3)				
5	30 (28.0)				

SD: standard deviation, n: number, cm: centimetres, %: percentage, DRU: Distal Radius and Ulna, *G: gamma's coefficient*

^ Goodman and Kruskal's gamma with Bonferroni correction

*Statistical significance at $p < 0.05$

radius grades ($p = 0.006$), ulna grades ($p = 0.025$), and Sanders stages ($p = 0.025$) (Table 3). PHOS stages were not associated with post-weaning curve progression ($p = 0.454$).

Discussion

Prompt weaning of brace treatment has benefits of reducing mental burden and avoidance of complications with prolonged brace-wear [9, 32–34]. Skeletal bone age guides our decision making to identify the earliest yet safe time point for stopping brace-wear. Having skeletal maturity indices

Table 2 Intergroup comparison of curve magnitude at brace weaning for each skeletal maturity index

Skeletal maturity at weaning	Brace weaning curve magnitude of major curves mean (SD), degree				p value^	For progression cases magnitude of curve progression mean (SD), degree
	n	Curve progression	n	No curve progression		
Whole cohort	13	41.4 (6.6)	94	34.8 (7.2)	0.004*	7.6 (2.2)
Risser staging						
4	5	35.2 (6.1)	26	35.2 (8.1)	0.914	7.0 (1.8)
4+	7	44.7 (2.9)	55	34.3 (7.4)	0.001*	8.2 (2.4)
5	1	49.0	13	36.2 (4.0)	0.106	6.1
DRU classification radius grade						
8	0	–	1	29.4	–	
9	10	42.0 (6.8)	33	32.9 (7.3)	0.004*	7.9 (2.3)
10	3	39.3 (7.0)	44	35.7 (7.4)	0.349	6.8 (1.7)
11	0	–	16	36.7 (6.3)	–	
Ulna grade						
7	6	39.1 (7.6)	16	31.5 (8.0)	0.060	7.3 (1.8)
8	7	43.3 (5.6)	58	34.9 (7.4)	0.007*	7.8 (2.5)
9	0	–	20	37.1 (4.9)	–	
Proximal humeral ossification system						
3	3	37.3 (9.2)	17	35.6 (6.2)	0.958	7.6 (2.9)
4	8	41.4 (5.7)	49	34.2 (7.1)	0.007*	7.8 (2.2)
5	2	47.5 (2.1)	28	35.4 (8.1)	0.056	6.6 (0.6)
Sanders staging						
7a	6	39.1 (7.6)	16	31.5 (8.0)	0.060	7.3 (1.8)
7b	5	43.4 (6.5)	22	33.7 (6.5)	0.016*	8.5 (2.5)
8	2	43.0 (4.2)	56	36.2 (7.0)	0.130	6.2 (2.1)

^ Mann–Whitney *U* test with exact sig (2-sided test)

n: number, SD: standard deviation

*Statistical significance at $p < 0.05$

that are readily visible in nearby proximity of spine radiographs is advantageous for minimizing radiation exposure as additional bone age radiographs are avoided [35, 36]. Risser staging is the most used bone age staging system, as iliac apophysis can be visible and assessed readily for its ossification and fusion to the ilium on spine radiographs. By combining the American and European versions of Risser staging, Risser + system [37] is established as an 8-point system with the inclusion of triradiate cartilage maturity: Stage 0 − and 0 + with the respective open and closed triradiate cartilage, Stage 1, 2, 3, 3/4 representing the progressive ossification of iliac crest in quarters per stage (3/4 denotes 75–100% coverage), Stage 4 and 5 representing the start and complete fusion of iliac apophysis to the ilium respectively. Despite the introduction of triradiate cartilage maturity allows more accurate assessment of maturity in the acceleration growth phase prior to PHV, Risser staging is not effective in indicating the beginning of growth plateau [12]. Hence, this study examines the possibility of using the proximal humerus ossification, visible on the same spine radiograph, for guiding brace weaning. It must be proven to be capable of identifying the PHV and predict growth potential remaining in children without spinal deformity, as well as in their scoliosis peers [20].

By convention, our clinical decision making is successful based on the absence of major curve progression. In this cohort with a minimum of 2-years post-weaning follow-up, we have identified PHOS Stage 5 to be an adequate independent indication for brace-weaning for Cobb angle < 40° at the time of weaning based on curve progression rate. There is, however, a lack of significant overall association between PHOS stages with whether curve progressed post-weaning. This may be explained by higher curve progression rates when weaning large curves at PHOS Stage 4 (31.6%) than at Stage 3 (16.7%). The same was demonstrated when analyzing with the 30° threshold of weaning Cobb angle. This is unlike the trend of reducing curve progression rate with increasing skeletal maturity as observed with Sanders staging and DRU classification. The risk of scoliosis relates to the amount of remaining growth [38], and curve progression rate should be lower as maturity advances and remaining growth potential reduces. This inconsistency may be due

Table 3 Test for associations of parameters and whether curve progressed after weaning

Progression rate (%) within each maturity grade

Maturity grading at weaning	Curve magnitude at weaning							
	< 30°		**≥ 30°**		**< 40°**		**≥ 40°**	
	Curve Progression	Non-Pro-gress-ion	Curve Pro-gression	Non-Pro-gress-ion	Curve Pro gression	Non-Pro-gress-ion	Curve Pro-gression	Non-Pro-gress-ion
Risser 4	0	100	20.8	79.2	18.2	81.8	11.1	88.9
Risser 4 +	0	100	16.7	83.3	0	100	29.2	70.9
Risser 5	0	100	7.7	92.3	0	100	50.0	50.0
R8	0	100	n = 0	n = 0	0	100	n = 0	n = 0
R9	0	100	32.3	67.7	10.0	90.0	53.8	46.2
R10	0	100	8.2	91.2	3.3	96.7	11.8	88.2
R11	0	100	0	100	0	100	0	100
U7	0	100	40.0	60.0	17.6	82.4	60.0	40.0
U8	0	100	15.2	84.8	2.4	97.6	26.1	73.9
U9	0	100	0	100	0	100	0	100
PHOS3	0	100	17.6	82.4	14.3	85.7	16.7	83.3
PHOS4	0	100	19.5	80.5	5.3	94.7	31.6	68.4
PHOS5	0	100	9.50	90.5	0	100	20.0	80.0
SS7a	0	100	40	60	17.6	82.4	60.0	40.0
SS7b	0	100	26.3	73.7	5.6	94.4	44.4	55.6
SS8	0	100	4.4	95.6	0	100	9.5	90.5

Parameters	Test for associations with curve progression after weaning (Yes/No)	
Continuous variable	Correlation coefficient (r_{pb}[§])	p value
Age at weaning	− 0.061	0.531
Months post-menarche	− 0.238	0.021*
Cobb angle at brace weaning	0.290	0.002*
Categorical variable	χ^2 statistics^	
Gender	0.307	0.580
Weaning protocol	0.543	0.545
Curve magnitude at weaning		
< 30° vs ≥ 30°	8.508	0.015*
< 40° vs ≥ 40°	8.357	0.009*
Curve type (thoracic/lumbar)	1.072	0.301

Skeletal maturity at weaning^	χ^2 statistics	p value	χ^2 statistics	p-value	Overall p-value for the maturity index
	Curve magnitude at weaning				
	< 30°		**≥ 30°**		
Risser stages	No progression cases		1.188	0.597	0.764
DRU classification Radius grades			11.370	0.004*	0.015*
Ulna grades			11.225	0.004*	0.016*
PHOS stages			1.125	0.665	0.630
Sanders stages			12.195	0.002*	0.007*
	< 40°		**≥ 40°**		
Risser stages	10.034	0.007*	1.528	0.243	0.307
DRU classification Radius grades	1.782	0.210	8.554	0.006*	0.006*
Ulna grades	5.056	0.039*	3.149	0.095	0.025*
PHOS stages	2.014	0.168	0.334	0.507	0.454
Sanders stages	5.056	0.039*	3.149	0.095	0.025*

[§]point-biserial correlation test

^maximum likelihood ratio Chi-square test with Fisher's exact test when expected cell count < 5

[*]Statistical significance at $p < 0.05$

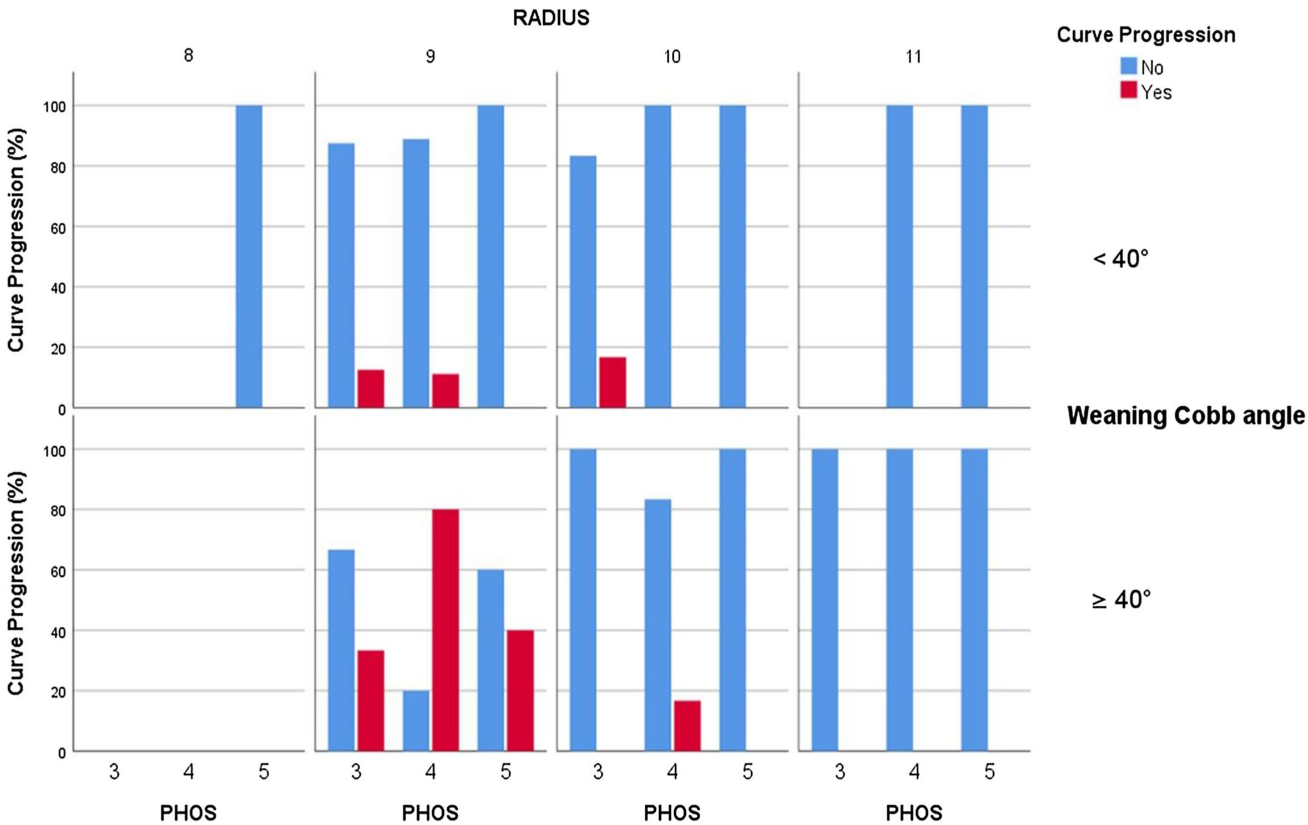


Fig. 3 Curve progression rate (%) with PHOS stages cross-referencing with radius grades of the Distal Radius and Ulna classification

to the smaller number of PHOS Stage 3 cases as compared to PHOS Stage 4 in this study. Nevertheless, it is clear that for curves < 40°, PHOS Stage 5 is a safe indication for brace weaning.

The sensitivity of using PHOS Stage 5 alone for weaning at large curves ≥ 40° is poor with up to 20% curve progression rate. As PHOS Stage 5 is the final stage of the classification, it has reduced capacity for assessing finer periods during the end of growth as compared to the DRU classification. Hence, our results suggest that additional assessment with the radial physes namely R10 is useful for further delineation. This is consistent with previous AIS studies whereby large curves often demonstrated curve progression despite end of skeletal growth assessment and the indication for weaning is different as compared to small curves [6, 27]. Similarly, the utilization of a single maturity parameter to decide brace weaning for these patients with high risk of continued progression after weaning is not advised. In such situations, using additional parameters especially those with multiple grades in assessing the end of skeletal growth is warranted [17]. These include the modified Sanders Stage 7 and DRU classification [6, 17, 27]. Our results therefore provided evidence that the utilization of radius grade 10 combined with PHOS Stage 5 is best for indicating the timing of weaning for large curves.

Accordingly, combining multiple maturity indices may be useful for earlier termination of brace-wear. Based on the moderately strong significant correlation between PHOS stages and radius gradings found in this study, further examination reveals that weaning brace-wear at PHOS Stage ≥ 4 is also possible to result in no curve progression, albeit for curves < 40°, if used with ≥ R10 (Fig. 3). The conjunctive assessment of the radial physes can allow reasonable reduction of brace weaning at earlier PHOS stages for small curves. This is particularly useful in cases whereby prolonging brace-wear is not recommended such as for those with an already long duration of brace-wear for relatively smaller curves and deteriorating brace compliance. Further brace-wear may lead to poor mental health and quality of life [32, 39, 40], reduced bone density [41], and back pain [32, 42]. Hence, PHOS Stage 5 is useful as an independent measure for only those with smaller curves. Multiple parameters are necessary for earlier weaning or for larger curves.

The limitations of this study include its limited sample size especially when examining boys and girls separately. However, since no association was observed between gender and curve progression, determination of weaning should not vary between sexes and thus is not considered when using maturity indices. This is consistent with the previous findings of Sanders et al. [43] who suggested that the pubertal growth rates are similar between boys and girls based on standardized skeletal maturity parameters. Another limitation is that the brace weaning protocol was not a set protocol in this study. However, there were no associations found between weaning protocol with curve progression or with the changes of Cobb angle, which were comparable between the gradual and immediate weaning patients. This should be addressed by a prospective validation study with standardized brace weaning protocol in the future.

The PHOS can be a useful skeletal maturity parameter for guiding brace weaning in the AIS population. Patients with curves < 40° do not experience further curve progression when weaned at PHOS Stage 5. For larger curves ≥ 40°, post-weaning curve progression can be avoided when brace-wear weaning is initiated at PHOS Stage 5 and ≥ R10. With the convenience of viewing on routine spine radiographs and reducing radiation exposure, the potential of utilizing the proximal humerus ossification for brace weaning, especially for small curves, should not be underestimated.

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Data availability The authors confirm that the data and materials of this study can be made available.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose. Each author certifies that he/she has no commercial associations that might pose a conflict of interest in connection with the submitted article.

Ethical approval Ethics approval was obtained from the Institutional Review Board of the University of Hong Kong/Hospital Authority Hong Kong West Cluster (HKU/HA HKW IRB), Reference Number: UW 16–288. This study was performed in line with the principles of the Declaration of Helsinki, and there were no deviations from routine care.

Consent to participate Both verbal and written informed consent were obtained from the parents and the patients.

Consent to publish The authors affirm that research participants provided informed consent for publication of their data.

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