

When Should We Wean Bracing for Adolescent Idiopathic Scoliosis?

Running Title: Redefining Brace Weaning Guidelines

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1 Abstract

2 *Background* Current brace weaning criteria for adolescents with idiopathic scoliosis (AIS) are
 3 not well defined. Risser Stage 4, ≤ 2 years since the onset of menarche, and no further increase in
 4 body height over 6 months are considered justifications for continued bracing. However, despite
 5 adherence to such standards, curve progression still occurs in some patients, and so better criteria
 6 for brace discontinuation are needed.

7 *Questions/purposes* (1) Is no change in height measurements over 6 months and Risser Stage 4
 8 sufficient for initiating brace weaning? (2) What is the association of larger curves (45°) at brace
 9 weaning on the progression risk? (3) Are a more advanced Risser stage, Sanders stage, or distal
 10 radius and ulna classification associated with a decreased risk of curve progression? (4) When
 11 should we wean patients with AIS off bracing to reduce the time for brace wear while limiting
 12 the risk of postweaning curve progression?

13 *Methods* All AIS patients who were weaned off their braces from June 2014 to March 2016 were
 14 prospectively recruited and followed up for at least 2 years after weaning. A total of 144 patients
 15 were recruited with mean followup of 36 ± 21 months. No patients were lost to followup.
 16 Patients were referred for brace weaning based on the following criteria: they were Risser Stage
 17 4, did not grow in height in the past 6 months of followup, and were at least 2 years
 18 postmenarche. Skeletal maturity was assessed with Risser staging, Sanders staging, and the distal
 19 radius and ulna classification. Curve progression was determined as any $> 5^\circ$ increase in the
 20 Cobb angle between two measurements between any subsequent six monthly followup visits. All
 21 radiographic measurements were performed by spine surgeons independently as part of their

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routine consultations, without knowledge of this study. Statistical analyses included an intergroup comparison of patients with and without curve progression, binomial stepwise logistic regression analysis, odds ratios (ORs) with their 95% confidence intervals (CIs), and a risk-ratio calculation. A reasonable protective maturity stage would generate an OR < 1.

Results Among patients braced until they had no change in height for 6 months, were 2 years post-menarche for girls, and Risser Stage 4, 29% experienced curve progression after brace weaning. Large curves ($\geq 45^\circ$) were associated with greater curve progression (OR, 5.0; 95% CI, 1.7–14.8; $p = 0.002$) as an independent risk factor. Patients weaned at Sanders Stage 7 (OR, 4.7; 95% CI, 2.1–10.7; $p < 0.001$), radius Grade 9 (OR, 3.9; 95% CI, 1.75–8.51; $p = 0.001$), and ulna Grade 7 (OR, 3.1; 95% CI, 1.27–7.38; $p = 0.013$) were more likely to experience curve progression. The earliest maturity indices with a reasonable protective association were Sanders Stage 8 (OR, 0.21; 95% CI, 0.09–0.48; $p < 0.001$), and radius Grade 10 (OR, 0.42; 95% CI, 0.19–0.97; $p = 0.042$) with ulna Grade 9 (no patients with curve progression).

Conclusion Brace weaning indications using Risser staging are inadequate. Curve progression is expected in patients with large curves, irrespective of maturity status. Bone age measurement by either Sanders staging or the distal radius and ulna classification provides clearer guidelines for brace weaning, resulting in the least postweaning curve progression. Weaning in patients with Sanders Stage 8 and radius Grade 10/ulna Grade 9 provides the earliest and most protective timepoints for initiating brace weaning.

Level of Evidence Level II, prognostic study.

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Introduction

The most frequently used and evidence-based method to prevent curve progression in adolescent idiopathic scoliosis (AIS) is bracing [41]. Despite the benefits of bracing, prolonged and indiscriminate use in children has been shown to reduce spinal mobility, lead to poor body image and self-esteem, and worse self-perception of function, pain, appearance, and mental health [13, 14, 17, 29, 30, 37, 38]. Treatment for AIS should be considered successful only if good patient-perceived outcomes are achieved in addition to preventing curve progression [15, 16, 43]. Hence, it is important to reduce unnecessary brace wear by limiting its use to only the period in which there is a risk of curve progression.

The growth potential of a patient with AIS determines the risk of curve progression. The greatest risk occurs during the pubertal growth spurt [12], and multiple radiological parameters exist to predict this timepoint [6, 7, 10, 11, 19, 33, 34, 36]. However, the risk of progression still exists throughout the adolescent growth period until skeletal maturity. To standardize when brace wear should be initiated, the Scoliosis Research Society (SRS) has created treatment guidelines [32]. However, no such guidelines exist for when brace wear should be terminated because the onset of skeletal maturity determined by growth parameters is not well understood. Stopping brace treatment when growth stops prevents overuse [22, 23, 31]. One study suggested that brace weaning may be initiated in patients with a Risser Stage of 4, those who are 12 months postmenarche, and those with lack of growth in height [4]. Another study recommended weaning in patients with a Risser Stage ≥ 4 , those who are more than 2 years postmenarche, and those with no growth between two visits of unknown duration [35]. However, both studies observed that some patients had curve progression beyond brace weaning, suggesting that these weaning

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criteria are imperfect. Therefore, we wished to investigate the risk of curve progression using various maturity parameters and to redefine brace-weaning criteria for patients with AIS, using standardized skeletal maturity parameters.

Specifically, we asked: (1) Is no change in height measurements over 6 months and Risser Stage 4 sufficient for initiating brace weaning? (2) What is the association of larger curves (45°) at brace weaning on the progression risk? (3) Are a more-advanced Risser stage, Sanders stage, or distal radius and ulna classification associated with a decreased risk of curve progression? (4) When should we wean patients with AIS off bracing to reduce the time for brace wear while limiting the risk of postweaning curve progression?

Patients and Methods

Study Design

This was a prospective study of all patients with AIS at our institution who underwent brace weaning during the period between June 2014 and February 2016. Patients were referred for brace weaning based on the following criteria: they were Risser Stage 4, had no growth in body height or arm span in the past 6 months of followup, and were at least 2 years postmenarche. The Risser staging is based on the ossification stages of the right iliac crest. Stage 0 indicates no ossification, stage 1 indicates ossification of the anterior lateral quarter, stage 3 indicates ossification of the anterolateral half, stage 3 indicates ossification of the anterior three-quarters, stage 4 indicates complete ossification, stage 4+ indicates capped apophysis, and stage 5 indicates complete fusion. We chose 6 months of followup and 2 years postmenarche as more stringent criteria for brace weaning. All patients were followed up for at least 2 years after they

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were weaned off their braces, with interval followup assessments every 6 months to identify any postweaning deterioration. None were lost to followup.

In our institution, all patients with AIS are administered a brace according to the following standardized brace referral criteria, as suggested by the SRS [32]: initial age between 10 and 14 years, major curve magnitude of 25°-40°, less than 1 year postmenarche, Risser Stages 0 to 2, and no treatment history. The mean Cobb angle before brace treatment initiation was $32 \pm 5^\circ$. All patients are prescribed an underarm (Boston) bracing.

For our recruited patients, all reported that they used their brace for more than 16 hours at the time of weaning, and they had regular recent visits to an orthotist for brace assessments. To maintain consistency of brace weaning for our recruited patients, our exclusions criteria were anyone who did not adhere to our brace weaning protocol, who had measured growth gain during the followup period after brace weaning, and those who were unable to complete the followup protocol. Braces were discarded on the day of brace weaning to avoid further use and to adhere to our study protocol. All 144 patients ready for brace weaning were recruited during this study period and none of the patients were lost to followup. All patients adhered to our study protocol. Hence, no patient was excluded from the study (Table 1). Our local institutional review board approved the study protocol.

Sample Size Calculation and Power Analysis

We used the guidelines based on the work of Hsieh et al. [21] to determine the a priori sample size calculation for logistic regression using G*Power (version 3.1.9.2; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). Based on the results of 0.11 (minimal curve

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progression rate in large curves: 16 of 144 patients), a sample size of 126 is adequate to achieve $\alpha = 0.05$ and power of 0.8. Post-hoc analysis was also performed and determined the power (0.82–0.96; $\alpha = 0.05$) to be satisfactory for all produced ORs.

Outcome Measures

At baseline (the date of recruitment or brace weaning), we collected data on the following parameters: body height, sitting height and arm span measured in centimeters, magnitude of the major coronal Cobb angle, Lenke classification and location of major curve (thoracic or thoracolumbar/lumbar), timing of menarche, Risser stage [2], and bone age assessment via Sanders staging [34], as well as the distal radius and ulna classification [8, 9]. The Risser Stages (Fig. 1) were 4, 4+, and 5 based on the ossification of the iliac apophysis. Risser Stage 4+ was defined as capping of the apophysis and was included for further grade segregation. The Sanders Stages ranged from 1 to 8, and the distal radius and ulna classification was divided into radius Grades 1 to 11 and ulna Grades 1 to 9. Sanders staging is a simplified method to measure bone age by assessment of the epiphyseal-metaphyseal bone complexes of all digits in the hand and radius. The distal radius and ulna classification measures bone age by appearance of the distal radius and ulna physis. Both systems consider capping of the epiphysis (digits, radius, or ulna) to indicate the pubertal growth spurt and closing of the physal plate to indicate skeletal maturity. However, each has a different set of grading specific to certain growth periods and hence one Sanders staging may coincide with multiple different radius or ulna grades. For example, a patient with Sanders 7 could also be classified as radius Grade 9 and ulna Grade 8 (Fig. 2) or as radius Grade 10 and ulna Grade 9 (Fig. 3). Standing whole-spine posteroanterior radiographs were obtained to measure the Cobb angles and Risser stages. For the baseline radiograph, all

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patients stopped using the brace for at least 24 hours beforehand to allow proper rebound to the real Cobb angle. In the same setting, a radiograph of the left hand and wrist was obtained to assess the bone age. Subsequently, at the other followup timepoints, height, arm span, and the Cobb angle were also measured. A designated clinic nurse who usually performs these tasks at our scoliosis clinic obtained all height and arm span measurements. These measurements were necessary to prove there was no further growth, and any patient with further growth was excluded from the study analyses. All radiographic measurements were performed by spine surgeons independently as part of their routine consultations, without knowledge of this study.

Statistical Analysis

Descriptive statistics for measurements are presented as the mean \pm SD. Curve progression was determined as any $> 5^\circ$ increase in the Cobb angle between two measurements during the subsequent followup visits. Statistical analyses included an intergroup comparison of patients with curve progression and those without, for which we used an independent samples t-test and nonparametric Mann-Whitney U test for age, curve type and the Cobb angle at the time patients were weaned off their braces. We set the cutoff angle for larger curves as $\geq 45^\circ$ [40, 42], if measured at the time of weaning, and we specifically assessed larger curves as a risk factor for progression, in addition to maturity grading.

We performed a chi-square test of independence [27] to test for any association between curve progression and sex, and curve magnitude ($< 45^\circ$ or $\geq 45^\circ$) as well as each skeletal maturity index. The relationship of curve magnitude at weaning and curve progression was tested using point-biserial correlation test. Based on these results from the bivariate analyses, in which any

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parameters having associations ($p < 0.2$) [18] with curve progression were identified, these parameters were then included in a subsequent regression analyses.

We performed a binomial logistic regression analysis to determine the associations of these parameters on the likelihood of curve progression. ORs per maturity index grading system were used to predict the risk of postweaning curve progression, given that statistically significant regression models were established. We performed step-wise logistic regression analyses to assess the individual associations of associated factors on curve progression, before examining these factors together as covariates. Covariates used for the multivariate model included a large curve magnitude and gender. Within each individual maturity index, we assessed the relative risk (RR) for various grades or stages. In addition, Cobb angle as a continuous variable was also used for multivariate analyses with covariates of each skeletal maturity grade and gender. Relationships between the various maturity indices were mapped to show the interactions with regards to curve progression rate (Fig. 4). Because Sanders stage 8 was the highest grade in the classification system, we used it to illustrate the change in the risk of curve progression from radius Grades 10 and 11, and from ulna Grades 7 to 9. Statistical significance was set at $p < 0.05$, and 95% CIs are reported. Data analyses were conducted using SPSS Windows 23.0 (IBM SPSS Inc, Chicago, IL, USA).

Results

Up to 29% (42 of 144) of patients still experienced curve progression after brace weaning despite being 2 years postmenarche for girls, Risser stage 4, and having no height gain for the previous 6 months. Most patients who were weaned had a Risser stage of 4+ (57%; 82 of 144), followed by

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those with radius Grade 9 or 10 (85%; 123 of 144), those with ulna Grade 8 (64%; 92 of 144), and those with Sanders Stage 8 (55%; 79 of 144). The mean degree of curve progression after weaning was $8.3 \pm 3.0^\circ$. No association was identified between curve type and curve progression ($p = 0.094$).

Patients with larger curve magnitudes ($\geq 45^\circ$) at the time of brace weaning was associated with a greater risk of further $>5^\circ$ of curve progression (OR, 5.0; 95% CI, 1.7–14.8; $p = 0.002$). Among the patients with large curves (those $\geq 45^\circ$ at the time of brace weaning), 63% (10 of 16) experienced curve progression (Table 2). A difference in Cobb angle between those who experienced curve progression and those who did not was observed (37.4° versus 34.7° , $p = 0.047$) (Table 3). Specifically testing curve magnitude in relation to curve progression, the correlation coefficient was 0.166 ($p = 0.047$). Patients with lower maturity index grades (Sanders Stage 7, radius Grade 9, and ulna Grade 7) who experienced curve progression had larger Cobb angles than did their counterparts without curve progression. No differences were observed for the Risser stages. The overall change in Cobb angle for these 16 patients with large curves was $6.3 \pm 3.5^\circ$. For their outcomes, 44% (7 of 16) were still under observation and 56% (nine of 16) were offered surgery.

Curve progression rates were lower for patients in the advanced stages of maturity including Risser Stage 5, Sanders Stage 8, radius Grade 11 and ulna Grade 9 (Table 4). However, curve progression was still observed in patients with Risser stage 5. Hence, no statistically significant model could be generated for Risser staging. For patients weaned at earlier stages Sanders stage 7 (OR, 4.7; 95% CI, 2.1–10.7; $p < 0.001$), radius Grade 9 (OR, 3.9; 95% CI, 1.75–8.51; $p = 0.001$), and ulna Grade 7 (OR, 3.1; 95% CI, 1.27–7.38; $p = 0.013$) were more likely to

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experience curve progression (Table 5). Using Cobb angle as a continuous variable, we observed similar findings with reduced OR with advancing maturity grades (Table 6). Regarding Sanders staging, 46% (30 of 65) experienced curve progression with stage 7 at the time of weaning while only 15% (12 of 79) of patients with Stage 8 experienced curve progression. In an independent observation of the distal radius and ulna classification, 45% (28 of 62) of patients weaned at radius Grade 9 and 48% (14 of 29) of patients weaned at ulna Grade 7 had curve progression. The progression rate reduced to 20% (12 of 61) for radius Grade 10 and 30% (28 of 92) for ulna Grade 8. For the interactions between different maturity parameters, any of the Sanders Stages (7 and 8) and distal radius and ulna classification (radius Grades 8 to 11 and ulna Grades 7 to 9) grades coexisted with Risser stage 4, 4+, and 5. No radius Grade 10 or 11, or ulna Grade 9 were observed in those with Sanders Stage 7 (Table 4) and hence were used to further segregate Sanders Stage 8 into different stages (Fig. 4).

Brace wear weaning at Sanders Stage 8 (OR, 0.21; 95% CI, 0.09–0.48), and radius Grade 10 (OR, 0.42; 95% CI, 0.19 to 0.97) and ulna Grade 9 (no patients with curve progression) provided the most protective association for any further curve progression (Table 5). Ulna Grade 8 had a borderline protective association, with an OR of 1.07 ($p > 0.05$). Based on the adjusted RR between individual maturity stages (Table 7), brace weaning at Sanders Stage 7 was associated with (OR: 4.73; 95% CI, 2.09–10.72; $p < 0.001$) curve progression as compared with Stage 8. Brace weaning at radius Grade 9 was associated with (OR, 3.29; 95% CI, 1.43–7.59; $p = 0.005$) curve progression as compared to Grade 10. Radius Grade 10 was the earliest grade at which we observed a 0% progression rate when combined with either Risser Stage 4 and ulna Grade 9 or with Risser Stage 4+ and ulna Grade 7. No patients experienced curve progression when weaned

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214 at stages radius Grade 10 and ulna Grade 9, or those with radius Grade 11.

215 **Discussion**

216 Although bracing has proven benefits for preventing curve progression in AIS, it should not be
 217 used indiscriminately as prolonged brace treatment may lead to spinal stiffness and poor self-
 218 esteem and self-perceived body image [13, 37, 38]. Bracing should be weaned as close to growth
 219 cessation as possible to reduce the risk of curve progression and that of prolonged brace
 220 treatment. Our ability to correctly determine skeletal maturity is crucial for accomplishing this.
 221 The traditional guidelines for brace weaning—Risser stage 4, no height gain within 6 months of
 222 followup, and being at least 2 years postmenarche for girls—are inadequate as our study suggests
 223 that nearly one-third of patients still experience curve progression after brace weaning. Although
 224 curve progression is expected in patients with large curves irrespective of maturity status, bone
 225 age assessment with either the Sanders staging or the distal radius and ulna classification
 226 provides clearer indicators for when braces should be weaned. Weaning at Sanders Stage 8 and
 227 radius Grade 10/ulna Grade 9 results in the least amount of curve progression after weaning.

228 A main limitation of this study is the uneven distribution of grades in each classification system.
 229 Some grade combinations, such as Risser Stage 5, Sanders Stage 8, radius Grade 10, and ulna
 230 Grade 7 lack data for comparison. Although this factor limits the extent of comparative data, it
 231 also reveals the intimate relationship among the studied maturity parameters. Another limitation
 232 is the lack of information on the apical rotation of the curves and flexibility. These may both
 233 influence risk of further curve progression. Although we applied a standardized protocol of
 234 bracing, assessments, and weaning criteria, there were variations in the timing of bracing and its

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association with changing curve behavior. The degree of vertebral wedging and rotation may also influence the risk of future curve progression and should be addressed in a further study.

Despite our decision to include only patients who adhered to the bracing protocol before

weaning, this information was self-reported and may be subject to skepticism. The use of 2-year followup in this study may not necessarily indicate skeletal maturity. Nevertheless, as there were no further height gain observed, it is likely that no further spine growth has occurred.

Furthermore, patients' bracing compliance before weaning was self-reported and there may be

concerns regarding its accuracy. This may affect the influence of stated maturity parameters in predicting further curve progression. The time of brace wear may also be important as it may affect changes in curve flexibility. A stiffer spine may be less susceptible to curve progression.

Whether the brace may have improved the curve magnitude and hence changed the natural history of disease is also unknown.

The current brace-weaning approaches (no height gain measurements, 2 years postmenarche, and Risser stage 4) are flawed because the curve progression rate in this study was still substantial (42 of 144 [29%]). Height measurements only reflect previous growth rates and are not useful for predicting future growth. Body height and arm span are frequently used to indicate growth, but neither truly represents spine growth. A previous study has identified mismatches between growth rates and curve progression rates, suggesting that body height changes do not fully reflect spine growth [11]. Sitting height eliminates the lower limb component, but it still does not directly represent spine growth. It is also easily affected by changes in curve magnitude.

Although we used body height, sitting height, and arm span measurements as stringent criteria for study inclusion, curve progression still occurred. Similarly, the use of menarche as a criterion

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is also flawed. It is markedly variable at onset, and delayed menarche is not uncommon [5].
 Risser staging is also inadequate to determine brace weaning because 75.2% of children continue
 to grow, despite apophyseal capping [20]. Some studies also suggested that the iliac apophysis
 may not fuse until adulthood, which limits the ability of Risser Stage 4 to represent remaining
 growth potential [24, 25, 39]. There is also evidence that children reach skeletal maturity earlier
 than past generations [3]. In essence, accurate bone age assessment is far more crucial for
 maturity assessment, and there is a greater need to rely on these radiological tools as compared
 with chronological age for initiating skeletal growth driven interventions.

We found that large curves ($\geq 45^\circ$) were an independent factor associated with curve progression
 after brace weaning. Specifically identifying the 45° cutoff appears to amplify this relationship as
 63% of patients with curves $\geq 45^\circ$ at the time of brace weaning had further progression,
 compared with only 25% of patients with curves $< 45^\circ$. It is important to note, however, that the
 difference in Cobb angle between patients with curve progression and those who did not was
 only minimal (37.4° vs 34.7°). Since all patients in this study were compared for this intergroup
 difference, it would have included patients of varying maturity status. The correlation between
 curve magnitude and curve progression was also small ($r_{pb} = 0.166$), which highlights this
 discrepancy. Nevertheless, it appears that the natural history or disease process dictates whether
 a curve continues to progress despite patients reaching skeletal maturity [40, 41] as curve
 progression is evident even in patients weaned at later maturity stages (Risser Stage 5 and
 Sanders Stage 8). Hence, it was crucial to control this covariate in the risk analysis. This also
 tends to confirm the findings suggested by Weinstein et al. [40, 42] regarding large curves of \geq
 45° . These findings further emphasizes the necessity for encouraging good brace compliance and

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early interventions. Aulisa et al. [1] has shown that long-term results of patients with 30° at the time of brace weaning do not deteriorate. For patients who do reach the threshold of 45° at the time of brace weaning should be warned of their poor prognosis to better manage expectations. This group of patients should be further studied to determine which curve type is at-risk of further deterioration and ultimately require surgical intervention.

Our analysis found that assessments of bone age with both Sanders staging and the distal radius and ulna classification provide better parameters for initiating brace weaning than Risser staging. Although Risser Stage 5 had an apparent protective association (OR, 0.68) at the time of brace weaning, there was still a 20% curve progression rate, and there were no differences between Risser Stage 5 and Stages 4 and 4+. Our findings are already some of the lowest curve progression rates reported with Risser staging based indications for brace weaning [1, 26, 35, 44]. Additionally, the timing of Risser Stage 5 does not appear to coincide chronologically compared with Sanders staging and distal radius and ulna classification. Such deviances have been identified before [28]. Any of the Sanders stages and radius and ulna grades may coexist with Risser Stages 4, 4+, or 5. There is no clear distinction or linear relationship between risk and protection for Risser staging. Capping of the apophysis (Risser Stage 4+) was added as an intervening stage between Risser Stages 4 and 5 to further segregate the growth stages and provide a more precise classification. However, this did not lead to a gradual reduction of the curve progression risk. Our testing reveals that the Risser staging system has a lack of consistency and accuracy, thus limiting its use for guiding brace weaning. As reported by Shi et al. [35] nearly 50% of patients experienced curve progression after brace weaning.

Based on our findings, we recommend using Sanders Stage 8, radius Grade 10, and ulna Grade 9

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301 as indicators for initiating brace weaning. There is clear distinction in OR for further curve
 302 progression between these and earlier stages. Although weaning should not be performed at
 303 Sanders Stage 7, curve progression was still observed in 15% of patients weaned at Stage 8.
 304 Alternatively, if patients continued to use a brace beyond Stage 8 to avoid this progression risk,
 305 there were no further grades for clinicians to monitor later maturity. In our study, 85% of patients
 306 without curve progression may have used a brace for longer than necessary. Because Sanders
 307 Stage 8 is the final stage of the classification system, its use is limited if the objective is to define
 308 the most precise guideline and wean patients as early as possible without the further risk of curve
 309 progression. Nevertheless, Sanders Stage 8 was shown to be protective, and the curve
 310 progression rate was relatively low. One of the main differences between the Sanders staging and
 311 the distal radius and ulna classification is the additional grade segregation during the growth
 312 cessation period. The distal radius and ulna classification has four radius Grades (8 to 11) and
 313 three ulna Grades (7 to 9) compared with only two Sanders stages. Hence, this may provide a
 314 finer scale for initiating brace weaning. Although no patients experienced further curve
 315 progression after achieving a radius Grade 11, it is unnecessary and not ideal to wean patients at
 316 the end grade because we aim to reduce the effective bracing time, and radius Grade 10 is
 317 already protective, with an OR of 0.42. The advantage of this system is using the ulna for the
 318 matched assessment, which helps reduce the progression risk further. Because of the limited
 319 number of patients with ulna Grade 7 within radius Grade 10, and because there was a residual
 320 progression risk in those with ulna Grade 8, it is not reliable to use these grades as indicators.
 321 There may always be some mismatch between radius and ulna grades; therefore, it is most
 322 appropriate to consider both radius Grade 10 and ulna Grade 9 as the earliest timepoint for

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initiating brace weaning with least curve progression risk. Despite our recommendations, our results need to be validated in other study populations. Whether curve type, degree of disc wedging, apical rotation and flexibility of the spine prior to bracing influences the accuracy of prediction for these various maturity indices remain to be explored. It is also important to note that spinal growth and height gain may have mismatches and the relationship between curve progression and growth near skeletal maturity should also be addressed [11].

Based on our findings, our study has three main implications. First, conventional recommendations [4, 35] based on clinical parameters, postmenarche years, and Risser staging are inadequate for preventing curve progression in patients with AIS after brace weaning. Second, bone age measurements of the hand and wrist supercede Risser staging as the maturity parameter to define growth cessation and the point of brace weaning. Either Sanders Stage 8 or radius Grade 10/ulna Grade 9 (Fig. 3) can be used to provide better indications for terminating brace treatment as compared with Risser staging. Both systems have a clear distinct grade where it becomes protective for any curve progression. Radius Grade 10/ulna Grade 9 has an additional advantage because it is not the end grade compared with Sanders Stage 8, which may provide an earlier and perhaps more precise timing for brace weaning. Finally, the association of large curves appears to be independent of maturity status, and patients should be warned of the risk of continued progression into adulthood with the risk of surgical intervention, even in patients in whom bracing was previously successful. Further long-term studies with other ethnic groups should be performed to validate our findings.

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Acknowledgments

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Legends



452 **Fig. 1** This x-ray demonstrates the appearance of Risser Stage 4, which is identified as
453 ossification of the whole length of the iliac apophysis that is not yet fused to the ilium.

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454

455 **Fig. 2** This x-ray shows Sanders Stage 7 with closure of all digital physes except for the distal
456 radius and ulna. On this same radiograph, the distal radius and ulna classification is considered
457 Radius Grade 9 (narrowing of the whole physal plate without fusion) and Ulna Grade 8 (fusion
458 of > 50% of the medial ulna physis).

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459

460 **Fig. 3** On this hand and wrist radiograph, the Sanders stage is still 7 because the distal radius
461 physis is white; however, for the distal radius and ulna classification, the radius grade is 10
462 (fused physis but scar still seen) while the ulna grade is 9 (complete fusion of the physeal plate).

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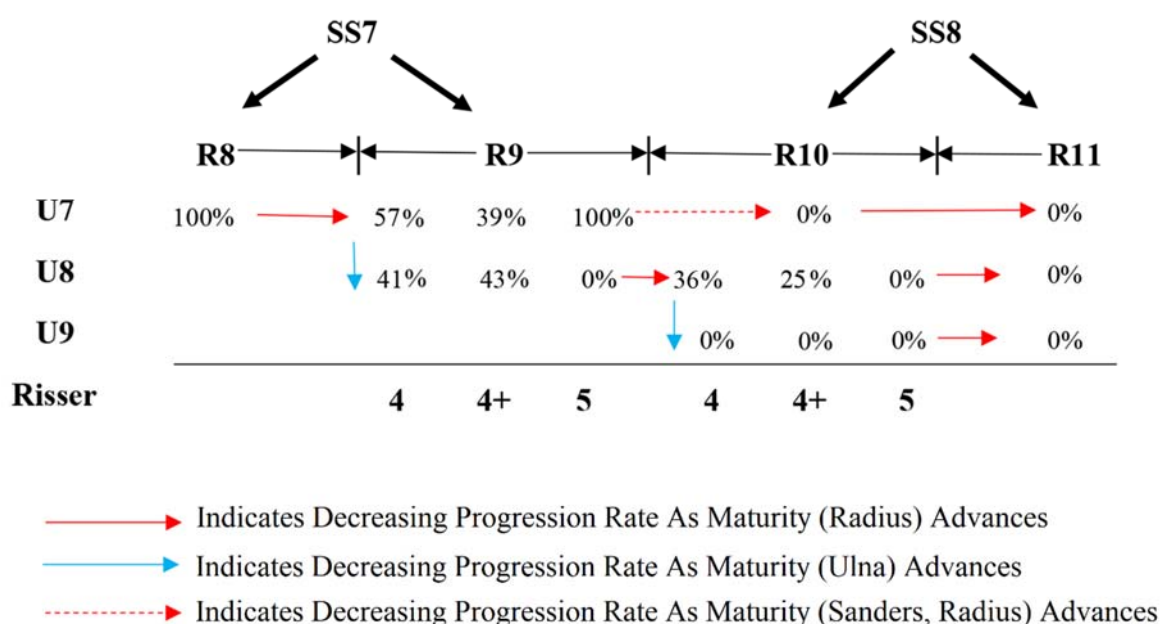


Fig. 4 We mapped the curve progression rate for Risser staging, Sanders staging and the distal radius and ulna classification. The arrows indicate the direction in reduction of curve progression rate with advancements in skeletal maturity. The curve progression rate was 0% in those with radius Grade 10/ulna Grade 7 and ulna Grade 9, Radius Grade 10/ulna Grade 8 in those with Risser Stage 5, and at radius Grade 11.

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Table 1. Patient baseline demographics at date of brace weaning decision

Parameters	Mean \pm SD		
	Total	Males	Females
Number of patients	144	23	121
Age (years)	14.8 \pm 1.1	15.8 \pm 0.8	14.6 \pm 1.0
Body height (cm)	161 \pm 7	169 \pm 7	160 \pm 5
Sitting height (cm)	86 \pm 4	89 \pm 2	85 \pm 4
Arm span (cm)	162 \pm 8	172 \pm 8	160 \pm 6
Cobb angle of major curve (°)	35.5 \pm 7.3	35.3 \pm 7.5	35.5 \pm 7.3
Number of months postmenarche at brace weaning			27.3 \pm 8.9
Age at menarche (years, Mean \pm SD)			12.3 \pm 1.1
Number of patients with large curves (Cobb angle of major curves $\geq 45^\circ$) n, %	16 (11%)		
Skeletal maturity parameters at baseline - n (%)			
Risser stage		Large curves ($\geq 45^\circ$) n (row %)	
4	42 (29)	5 (12)	
4+	82 (57)	9 (11)	
5	20 (14)	2 (10)	
Radius grade			
8	3 (2)	1 (33)	
9	62 (43)	9 (15)	
10	61 (42)	5 (8)	
11	18 (13)	1 (6)	
Ulna grade			
7	29 (20)	4 (14)	
8	92 (64)	11 (12)	
9	23 (16)	1 (4)	
Sanders stage			
7	65 (45)	10 (15)	
8	79 (55)	6 (8)	
Lenke curve types			
Type 1	18 (12.5)	2 (11.1)	
2	17 (11.8)	1 (5.9)	
3	42 (29.2)	8 (19.0)	
4	3 (2.1)	0	
5	17 (11.8)	0	
6	47 (32.6)	5 (10.6)	

SD: standard deviation, n: number of patients

Table 2. Comparison of curve magnitude at brace weaning for each skeletal maturity index

Curve progression		No curve progression	p value	Mean difference/ median difference	95% CI	Magnitude of curve progression (degrees, mean ± SD)
Brace weaning curve magnitude of major curve (degrees, mean ± SD)						
Risser Stage						
4	36.8 ± 6.8	34.5 ± 7.9	0.392	2.2	-2.6 to 7.1	7.8 ± 2.8
4+	37.3 ± 8.1	34.1 ± 7.1	0.069	3.2	-0.5 to 6.8	8.9 ± 3.2
5	40.4 ± 10.0	37.4 ± 4.5	0.554	3.0	-12.5 to 18.6	6.5 ± 1.5
Sanders Stage^						
7	38.0 ± 7.9	31.7 ± 6.6	0.001*	-7.3	-11.1 to -3.3	8.1 ± 2.7
8	35.7 ± 7.1	36.3 ± 6.8	0.672	-1.1	-6.0 to 3.7	8.3 ± 3.0
Distal radius and ulna Classification						
Radius ^						
8	46.5 ± 2.2	29.4 (n = 1)	1.000	-17.1	-18.6 to -15.5	12.1 ± 4.9
9	37.4 ± 7.9	31.8 ± 6.7	0.003*	-6.5	-10.4 to -2.6	7.8 ± 2.4
10	35.7 ± 7.1	35.8 ± 6.9	0.870	0.35	-4.3 to 6.0	8.6 ± 3.6
11		37.5 ± 6.3				
Ulna ^						
7	36.6 ± 9.4	30.8 ± 7.6	0.057	-6.8	-13.6 to 0.0	8.1 ± 3.1
8	37.7 ± 6.9	34.7 ± 7.2	0.087	-3.0	-6.4 to 0.5	8.3 ± 3.0
9		37.2 ± 4.8				

[^] Mann-Whitney *U* test, with Hodges-Lehmann median difference and its 95% CI, *significance level set at $p < 0.05$

SD: standard deviation; CI: confidence interval

Table 3. Comparison of curve progression and no curve progression patients

Parameters	Curve progression (n = 42)	No curve progression (n = 102)	p value		
Intergroup comparison for difference^					
Age (years, Mean ± SD)	14.6 ± 1.0	14.9 ± 1.1	0.097		
Cobb angle at brace weaning (degrees, mean ± SD)	37.4 ± 7.7	34.7 ± 7.0	0.047*		
Test for correlation and association of parameters with postweaning curve progression versus noncurve progression					
Correlation		r _{pb}	p value		
Curve magnitude in degrees ^v		0.166	0.047*		
Association				Odds	
Frequency#	n (%)		p value	Ratio	95% CI
Gender			0.175	0.5	(0.1, 1.4)
Females	38/121 (31)	83/121 (69)			
Males	4/23 (17)	19/23 (83)			
Curve magnitude			0.002*	5.0	(1.7, 14.8)
< 45°	32/128 (25)	96/128 (75)			
≥ 45°	10/16 (62.5)	6/16 (37.5)			
Skeletal maturity					
Risser Stage					
4			0.266	-	
4+	16/42 (38)	26/42 (62)			
5	22/82 (27)	60/82 (73)			
Sanders Stage	4/20 (20)	16/20 (80)			
SS7			< 0.001*	4.8	(2.2, 10.5)
SS8	30/65 (46)	35/65 (54)			
Distal radius and ulnaRU classification*	12/79 (15)	67/79 (85)			
Radius					
R8			< 0.001*	-	
R9	2/3 (67)	1/3 (33)			
R10	28/62 (45)	34/62 (55)			
R11	12/61 (20)	49/61 (80)			
Ulna	0	18 (100)			
U7			< 0.001*	-	
U8	14/29 (48)	15/29 (52)			
U9	28/92 (30)	64/92 (70)			
	0	23 (100)			

[^] independent samples t-test, Shapiro-Wilk p > 0.05; # Chi-square test of independence unless stated otherwise; ^v point-biserial correlation test, * maximum likelihood ratio Chi-square test, * statistical significance set at p < 0.05
SD: standard deviation; n: number

Table 4. Distribution of curve progression rates according to maturity indices

Sanders	Radius	Ulna	Rate of curve progression								
			Risser 4			Risser 4+			Risser 5		
			Total	Progressed	%	Total	Progressed	%	Total	Progressed	%
			n	n		n	n		n	n	
7	8	7	1	1	100	0	0	0	1	1	100
		9	7	4	57	13	5	39	3	3	100
		8	17	9	4	21	7	43	1	0	0
8	10	7	0	0	0	2	0	0	0	0	0
		8	11	4	36	32	8	25	6	0	0
		9	2	0	0	6	0	0	2	0	0
	11	7	0	0	0	1	0	0	0	0	0
		8	3	0	0	0	0	0	1	0	0
		9	3	0	0	12	0	0	8	0	0

n: number of patients

%; rate of curve progression (number of progressed cases/ total number of cases with the same Sanders, radius/ulna and Risser stages)

Table 5. Adjusted odds ratio for postweaning curve progression for individual skeletal maturity grades

Maturity indices at brace weaning	Grades			
Risser staging	Risser 4	Risser 4.5	Risser 5	
Adjusted OR [†] (95% CI)	1.87 (0.84 - 4.17, p > 0.05)	0.67 (0.31 - 1.45, p > 0.05)	0.68 (0.20 - 2.28, p > 0.05)	
Sanders staging	Sanders Stage 7	Sanders Stage 8		
Adjusted OR [†] (95% CI)	4.73* (2.09 - 10.72, p < 0.001)	0.21* (0.09 - 0.48, p < 0.001)		
DRU classification				
Radius	Radius 8	Radius 9	Radius 10	Radius 11
Adjusted OR [†] (95% CI)	7.23 (0.50 - 105.96, p > 0.05)	3.85* (1.75 - 8.51, p = 0.001)	0.42* (0.19 - 0.97, p = 0.042)	-
Ulna	Ulna 7	Ulna 8	Ulna 9	
Adjusted OR [†] (95% CI)	3.06* (1.27 - 7.38, p = 0.013)	1.07 (0.49 - 2.36, p > 0.05)		

*Statistical significance set at p < 0.05.

[†]Adjusted OR with covariates: Large curve at weaning (Cobb angle < 45°, ≥ 45°), gender

- undefined as there were no patients with curve progression.

OR = odds ratio; CI = confidence interval; DRU = distal radius and ulna.

Table 6. Multivariate analysis for postweaning curve progression for individual skeletal maturity grades based on Cobb angle as a continuous variable

Maturity indices at brace weaning	Risk factors	Regression coefficient	Wald X ²	p value	Odds ratio	95% CI
Sanders	Weaning at SS7	1.766	17.241	< 0.001*	5.85	2.54-13.45
	Cobb at weaning	0.071	6.230	0.013*	1.07	1.02-1.14
	Gender	0.888	1.937	0.164	2.43	0.70-8.49
	Weaning at SS8	-1.766	17.241	<0.001*	0.17	0.074-0.39
	Cobb at weaning	0.071	6.230	0.013*	1.07	1.02-1.14
	Sex	0.888	1.937	0.164	2.43	0.70-8.49
	Risk factors	Regression coefficient	Wald X ²	p value	Odds ratio	95% CI
Radius	Weaning at R8	2.053	1.387	0.139	7.79	0.51-117.98
	Cobb at weaning	0.048	3.238	0.072	1.05	1.00-1.11
	Sex	1.052	2.559	0.110	2.86	0.79-10.39
	Weaning at R9	1.583	14.492	< 0.001*	4.87	2.16-11.00
	Cobb at weaning	0.073	6.444	0.011*	1.08	1.02-1.14
	Gender	0.713	1.296	0.255	2.04	0.60-6.97
	Weaning at R10	-0.918	5.135	0.023*	0.40	0.18-0.88
	Cobb at weaning	0.055	4.298	0.038*	1.06	1.00-1.11
	Sex	0.853	2.014	0.156	2.35	0.72-7.63
	Weaning at R11	-	-	-	-	
	Cobb at weaning					
	Sex					
	Risk factors	Regression coefficient	Wald X ²	p value	Odds Ratio	95% CI
Ulna	Weaning at U7	1.303	7.969	0.005*	3.68	1.49-9.09

	Cobb at weaning	0.064	5.526	0.019*	1.07	1.01-1.13
	Sex	0.898	2.092	0.148	2.45	0.73-8.28
	Weaning at U8	-0.097	0.060	0.807	0.91	0.42-1.97
	Cobb at weaning	0.052	3.841	0.050	1.05	1.00-1.11
	Sex	0.775	1.706	0.191	2.17	0.68-1.97
	Weaning at U9	-	-	-	-	
	Cobb at weaning					
	Sex					
	Risk factors	Regression coefficient	Wald X ²	p value	Odds ratio	95% CI
Risser	Weaning at Risser 4	0.625	2.425	0.119	1.87	0.85-4.10
	Cobb at weaning	0.053	3.938	0.047*	1.05	1.00-1.11
	Sex	0.801	1.819	0.177	2.23	0.70-7.14
	Weaning at Risser 4+	0.303	0.628	0.428	1.35	0.64-2.86
	Cobb at weaning	0.050	3.636	0.057	1.05	1.00-1.11
	Sex	0.859	2.054	0.152	2.36	0.73-7.64
	Weaning at Risser 5	-0.586	0.913	0.339	0.56	0.17-1.85
	Cobb at weaning	0.055	4.278	0.039	1.06	1.00-1.11
	Sex	0.675	1.261	0.261	1.96	0.61-6.38

*Statistical significance set at $p < 0.05$. Factors that are statistically significant are in bold.

- Undefined as there were no patients with curve progression.

CI = confidence interval, X² = Chi-square value.

Table 7. Relative risk and adjusted relative risk for skeletal maturity grades

Skeletal maturity index	RR	95% CI	p value	Adjusted RR [^]	95% CI	p value
Risser staging						
4 vs 4+	1.42	-	0.198	1.48	-	0.529
4+ vs 5	1.34	-	0.530	1.11	-	0.875
Sanders staging						
SS7 vs SS8	3.04*	1.70 – 5.45	< 0.001	4.73*	2.09 – 10.72	< 0.001
DRU classification						
radius						
R8 vs R9	1.48	-	0.466	2.99	-	0.434
R9 vs R10	2.30*	1.29 – 4.09	0.003	3.29*	1.43 – 7.59	0.005
R10 vs R11						
Ulna						
U7 vs U8	1.59	-	0.078	2.28	-	0.068
U8 vs U9						

* significant level at $p < 0.05$, [^] adjusted RR with covariates: large curve at weaning ($< 45^\circ$, $\geq 45^\circ$), gender

No RR generated for R11 and U9 as there were no cases with curve progression

RR: relative risk; CI: confidence interval; DRU: distal radius and ulna