Quantitative cervical vertebral maturation assessment in adolescents with normal occlusion: A mixed longitudinal study

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Introduction: The purpose of this study was to establish a quantitative cervical vertebral maturation (CVM) system for adolescents with normal occlusion. **Methods:** Mixed longitudinal data were used. The subjects included 87 children and adolescents from 8 to 18 years old with normal occlusion (32 boys, 55 girls) selected from 901 candidates. Sequential lateral cephalograms and hand-wrist films were taken once a year for 6 years. The lateral cephalograms of all subjects were divided into 11 maturation groups according to the Fishman skeletal maturity indicators. The morphologic characteristics of the second, third, and fourth cervical vertebrae at 11 developmental stages were measured and analyzed. **Results:** Three characteristic parameters (H4/W4, AH3/PH3, @2) were selected to determine the classification of CVM. With 3 morphologic variables, the quantitative CVM system including 4 maturational stages was established. An equation that can accurately estimate the maturation of the cervical vertebrae was established: CVM stage = −4.13 + 3.57 × H4/W4 + 4.07 × AH3/PH3 + 0.03 × @2. **Conclusions:** The quantitative CVM method is an efficient, objective, and relatively simple approach to assess the level of skeletal maturation during adolescence. (Am J Orthod Dentofacial Orthop 2008;134:720.e1-720.e7)

Bone age, as determined by hand-wrist radiographs and the Fishman skeletal maturity indicators (SMI), is a popular and reliable approach for evaluating skeletal maturation in orthodontic clinical practice.[1-3] However, this method requires a hand-wrist radiograph. Recently, the use of cervical vertebral maturation (CVM) has gained increasing interest as a valid replacement for hand-wrist evaluation.[4-7] The main advantage of the CVM evaluation is that it can be done with a conventional lateral cephalogram (LCR); this avoids the extra radiation exposure of a hand-wrist radiograph.

Evaluation of the maturational stages in the cervical vertebrae was originally developed by Lamparski[8] and successively implemented by O'Reilly and Yanniello[9] and Baccetti et al.[10] Nevertheless, almost all previous classifications with cervical vertebrae either used or referred to the atlas of Lamparski.[8] Compared with the hand-wrist evaluation, the cervical vertebrae have few indicators of skeletal maturity. The special signs of morphologic changes during growth are not as unique and identifiable as those of the hand and wrist, so that it is subjective and more difficult to evaluate the CVM by an atlas such as the hand-wrist radiograh. However, the shape and size of the vertebral bodies are relatively similar and regular, so it is feasible to evaluate skeletal maturation qualitatively and quantitatively by measuring parameters of the vertebral bodies.

To make the CVM analysis easier and more applicable to most patients, the following improvements will be needed: (1) use fewer vertebral bodies and more sensitive parameters to perform the staging, and the parameters should be only in the cervical vertebrae (C2-C4) that can be seen when the patient wears a protective radiation collar; and (2) avoid estimating the stages based on a comparative assessment of between-stage changes, and each stage should be identified easily in 1 cephalogram.

This study was conducted to accomplish these objectives. We established a quantitative CVM (QCVM) system. Every period of the QCVM has its definitive quantitative standard so that the skeletal maturation level can be evaluated both qualitatively and quantitatively.

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Table I. Demographic distribution of lateral cephalograms of the 11 groups according to the SMI (mean ± SD)

		Average age (y)		Age range (y)	
SMI	N	Girls	Boys	Girls	Boys
1	41	8.21 ± 1.07	9.21 ± 1.41	8.00-10.49	8.83-11.25
2	44	9.27 ± 1.02	10.13 ± 0.93	8.50-11.07	9.65-11.80
3	43	10.01 ± 1.50	11.29 ± 1.15	8.52-12.08	10.15-12.50
4	45	10.71 ± 0.45	11.61 ± 0.54	10.28-11.97	11.03-13.17
5	44	11.18 ± 1.19	12.28 ± 0.60	10.07-13.17	12.00-13.57
6	48	11.92 ± 1.46	12.81 ± 0.67	10.25-14.17	12.08-14.33
7	47	12.29 ± 0.91	13.65 ± 0.95	11.28-14.33	12.25-15.75
8	45	12.98 ± 0.61	14.19 ± 1.23	12.05-13.75	13.00-16.07
9	45	13.64 ± 1.20	15.17 ± 0.79	12.25-15.50	14.10-16.20
10	47	14.93 ± 0.90	16.22 ± 1.10	13.88-16.33	14.93-17.50
11	62	16.41 ± 1.39	17.60 ± 0.50	13.98-17.92	16.00-18.18

MATERIAL AND METHODS

Mixed longitudinal data were used. The samples included 87 children and adolescents (32 boys, 55 girls) from 8 to 18 years old with normal occlusion selected from 901 candidates. These subjects were divided into 2 groups according to the beginning age of observation. For group 1 (43 subjects; 16 boys, 27 girls), the beginning age was 8 to 9 years, and, for group 2 (44 subjects; 16 boys, 28 girls), it was 12 to 13 years. Sequential LCRs and hand-wrist films of all subjects were taken once a year for 6 years. Informed consent forms were obtained from all subjects and their parents. The study protocol was reviewed and approved by the Institutional Review Board of Peking University Health Science Center.

The selection criteria were (1) deciduous, mixed, or permanent dentition; (2) normal occlusion (<3 mm overjet, and overbite less than one-third coverage of mandibular incisor); (3) harmonious facial profile and competent lips at rest; and (4) no orthodontic treatment or dental extractions.

The LCRs and hand-wrist films of all subjects totaled 522, of which 4 films did not reach even SMI 1, and 7 films were discarded because of fuzziness. The remaining 511 LCRs were divided into 11 maturation groups by a calibrated technician (J.-H.J.) according to the Fishman SMIs assessed from their hand-wrist films, as shown in Table I. Complete details about SMI can be found elsewhere.[1,2]

The 42 morphologic characteristic parameters of C2, C3, and C4 in the LCRs at 11 developmental stages (SMI 1-11) were measured and analyzed. All points and lines, as shown in Figures 1 and 2 and defined in Table II, were traced with a pencil by 1 observer (L.-L.C.) under optimal conditions and then measured with micrometer calipers. The ratios of these parameters were calculated.

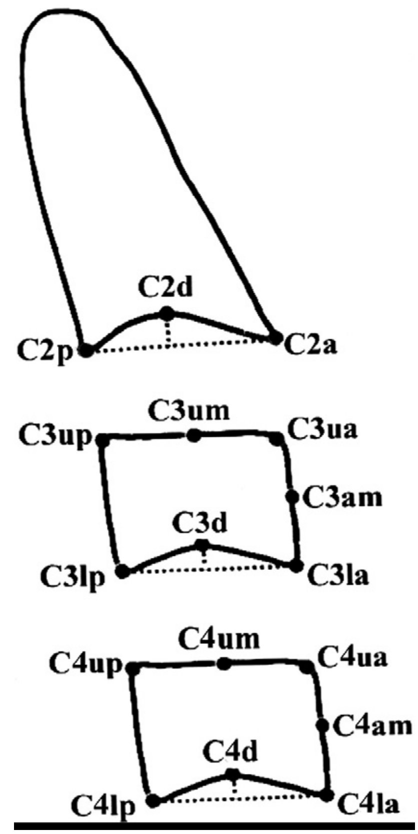

Fig 1. Measuring points used in the cephalometric analysis: *C2d, C3d,* and *C4d,* the most superior point of the lower border of the bodies of C2, C3, and C4, respectively; *C2a, C2p, C3la, C3lp, C4la,* and *C4lp,* the most posterior and most anterior points on the lower border of the bodies of C2, C3, and C4, respectively; *C3ua, C3up, C4ua,* and *C4up,* the most superior points of the posterior and anterior borders of the bodies of C3 and C4; *C3um* and *C4um,* the middle of the upper border of the bodies of C3 and C4; *C3am* and *C4am,* the middle of the anterior border of the bodies of C3 and C4.

Statistical analysis

The data were analyzed with statistical software (version 13.0, SPSS for Windows, SPSS, Chicago, Ill). The arithmetic mean and the standard deviation were calculated for each variable. The statistical analyses we used included LOESS smoothing, correlation coefficient (CC) analysis, and variable cluster analysis.

Intraobserver reliability and reproducibility of the measurements were checked on 20 randomly selected cephalometric radiographs that were retraced and

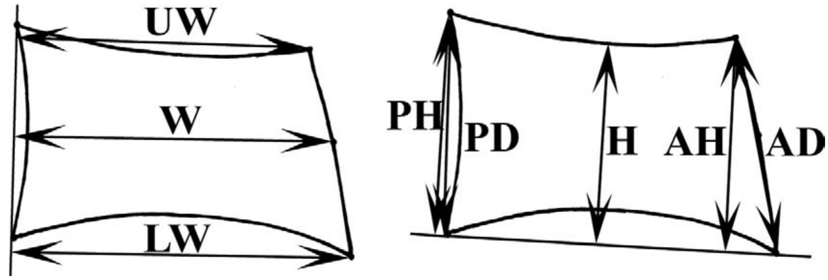

Fig 2. Measuring lines used in the cephalometric analysis. *UW*, Vertical distance of Cua to the connection of Cup and Clp; *W*, vertical distance of Cam to the connection of Cup and Clp; *LW*, vertical distance of Cla to the connection of Cup and Clp; *PH*, vertical distance of Cup to the connection of Clp and Cla; *H*, vertical distance of Cum to the connection of Clp and Cla; *AH*, vertical distance of Cua to the connection of Clp and Cla; *AD*, distance between Cla and Cua; *PD*, distance between Clp and Cup.

redigitized 2 weeks later. The method error did not exceed 0.2 mm for all linear variables.

RESULTS

After the LOESS smoothing (Fig 3), we found that, of the 42 parameters, 30 were positively correlated with SMI, 4 were negatively correlated, and 8 were not correlated (Table III).

The CC between 34 correlated parameters and the SMI was derived through CC analysis. These parameters were arranged in descending order according to the CC (Table IV).

Ten ratio and angle parameters whose CCs were higher than 0.85 were selected to calculate the CVM. These 10 parameters were divided into 3 categories after the variable cluster analysis (Table V). We chose the first 1 of each category (H4/W4, AH3/PH3, @2) to classify CVM.

According to SMI, SMI 1-11 can be divided into periods of accelerating velocity (SMI 1-3), high velocity (SMI 4-7), and decelerating velocity (SMI 8-11).[11-13] In this study, classification was simplified by using the character of SMI and fewer bony centers of cervical vertebrae. QCVM had only 4 stages: SMI 1-3 were merged into I (period of accelerating velocity), SMI 4-7 were merged into II (period of high velocity), SMI 8 and 9 were merged into III (period of decelerating velocity), and SMI 10 and 11 were merged into IV (period of completing velocity). The quantitative standard of every stage is shown in Table VI.

An equation that can accurately estimate the maturation of the cervical vertebrae was formed: CVM stage (CVMS) $= -4.13 + 3.57 \times$ H4/W4 $+ 4.07 \times$ AH3/PH3 $+ 0.03 \times$ @2.

By this equation, we can also determine that in QCVM I, CVMS <1.7404; in QCVM II, $1.7404<$ CVMS <2.623; in QCVM III, $2.623<$ CVMS <3.5199; and in QCVM IV, CVMS >3.5199.

DISCUSSION

The Fishman SMI had been found to be generally valid in both clinical and research situations. The system uses only 4 stages of bone maturation, all found at 6 anatomic sites. Eleven discrete adolescent SMIs, covering the entire period of adolescent development, were found on these 6 sites.

Many studies showed a strong correlation between skeletal maturation determined from hand-wrist radiographs and cervical vertebrae evaluation.[14-16] Flores-Mir et al[14] assessed the correlation between the SMI and the traditional CVM method proposed by Baccetti et al.[10] Flores-Mir et al[14] found that all correlation values were statistically different from zero ($P<0.024$) whether for early, average, or late maturing adolescents (early, 0.725; average, 0.698; late, 0.871). Our results agreed with that study. Of 42 parameters, 30 parameters were positively correlated with SMI, 4 were negatively correlated, and 8 were not correlated (Table III). The CCs were relatively high, of which the highest was 0.9107, and 23 were above 0.8008 (Table IV). The parameters of cervical vertebral width (UW, W, LW) had no correlation with SMI, whereas the ratios of cervical vertebral width, such as H4, W4 H3, and W3, had a strong correlation with SMI (0.9107 and 0.9091, respectively). The results indicated that the growth of cervical vertebral width had been almost completed during early cervical growth, and, in later growth, the morphologic changes of the cervical vertebrae were mainly increased height. In the first stage of maturation, the vertebral bodies were wedge shaped with the superior vertebral borders tapered from posterior to anterior. With growth, the vertebral bodies became

Table II. Measuring lines and ratios used in the cephalometric analysis

Parameter	*Description*
D2	Vertical distance of C2d to C2a and C2p connection
D3	Vertical distance of C3d to C3lp and C3la connection
D4	Vertical distance of C4d to C4lp and C4la connection
@2	Antero-superior angle of C2d-C2p connection to C2p-C2a connection
@3	Antero-superior angle of C3d-C3lp connection to C3lp-C3la connection
@4	Antero-superior angle of C4d-C4lp connection to C4lp-C4la connection
AI2-3	Distance between C2a and C3ua
PI2-3	Distance between C2p and C3up
AI3-4	Distance between C3la and C4ua
PI3-4	Distance between C3lp and C4up
PH3	Vertical distance of C3up to the connection of C3lp and C3la
H3	Vertical distance of C3um to the connection of C3lp and C3la
AH3	Vertical distance of C3ua to the connection of C3lp and C3la
AD3	Distance between C3la and C3ua
PD3	Distance between C3lp and C3up
UW3	Vertical distance of C3ua to the connection of C3up and C3lp
W3	Vertical distance of C3am to the connection of C3up and C3lp
LW3	Vertical distance of C3la to the connection of C3up and C3lp
AH3/H3	Ratio of AH3 to H3
H3/PH3	Ratio of H3 to PH3
AH3/PH3	Ratio of AH3 to PH3
AH3/W3	Ratio of AH3 to W3
H3/W3	Ratio of H3 to W3
PH3/W3	Ratio of PH3 to W3
UW3/LW3	Ratio of UW3 to LW3
AD3/PD3	Ratio of AD3 to PD3
PH4	Vertical distance of C4up to the connection of C4lp and C4la
H4	Vertical distance of C4um to the connection of C4lp and C4la
AH4	Vertical distance of C4ua to the connection of C4lp and C4la
AD4	Distance between C4la and C4ua
PD4	Distance between C4lp and C4up
UW4	Vertical distance of C4ua to the connection of C4up and C4lp
W4	Vertical distance of C4am to the connection of C4up and C4lp
LW4	Vertical distance of C4la to the connection of C4up and C4lp
AH4/H4	Ratio of AH4 to H4
H4/PH4	Ratio of H4 to PH4
AH4/PH4	Ratio of AH4 to PH4
AH4/W4	Ratio of AH4 to W4
H4/W4	Ratio of H4 to W4
PH4/W4	Ratio of PH4 to W4
UW4/LW4	Ratio of UW4 to LW4
AD4/PD4	Ratio of AD4 to PD4

rectangular, square, and finally rectangular, with height greater than width.

In our study, the Lamparski atlas[8] was not used or referred to. The Fishman SMI was applied as the gold standard for skeletal maturation evaluation. Based on the strong correlation between SMI and CVM, as well as easy identification and measurement of cephalometric landmarks of the cervical vertebrae, the new method of QCVM was established by using 3 definite and sensitive parameters. This new method was found to be feasible and meaningful in our study.

Selection of parameters of QCVM

The morphologic characteristic parameters of CVM were concavity of the lower border, and height and shape of the vertebral bodies. Three decisive variables (H4/W4, AH3/PH3, @2) of QCVM selected from the 42 parameters were similar to those of CVM but more definite. It would be more simple and accurate to use 3 parameters than to take all parameters into account.

Concavity of the lower border of the C2 (@2) was selected. In our study, @2 had a strong correlation with SMI (0.8617), and this agreed with other studies.[7-10] From SMI 1 to SMI 11, @2 increased gradually (3.37°, 10.14°, 15.28°, 22.09°) and was consistent with the generally accepted concept that, as maturation became greater, concavity was also higher.

C3 and C4 were also selected, and other cervical vertebrae were disregarded for various reasons: C1 (atlas) did not show the body, C2 (axis) showed little morphologic change and was difficult to measure, and C5 might not appear clearly on cephalometric radiographs.[17-20]

External environmental factors such as pressure, corporal position, or disease can influence the height of vertebral bodies. Facial pattern can also modify the height of the cervical vertebrae. In addition, considering the distortion and magnification of LCR, ratio and angle measurements would be better than linear measurements, both in comparability and validity. Thus, the parameters of ratio and angle were selected to calculate CVM; this meant that only the shape of the cervical vertebrae would be considered.

Compared with the traditional CVM system based on the Lamparski atlas,[8] the method of QCVM has several advantages.

The CVM, based on the Lamparski atlas,[8] was convenient but could not evaluate growth in an objective and definite manner. Every stage had many decisive morphologic features related to the classification, and sometimes those features would be confused. QCVM evaluates the morphologic features of only C2, C3, and C4. With LOESS smoothing, CC analysis, and

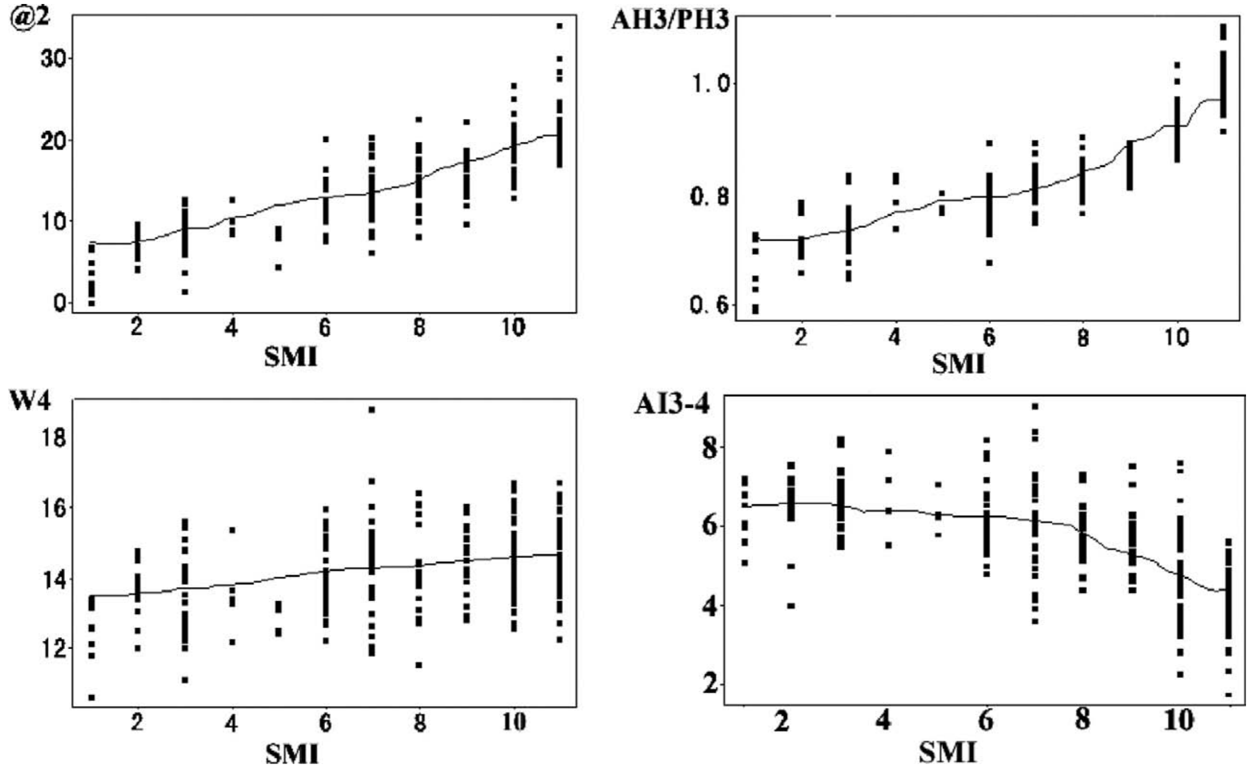

Fig 3. The LOESS smoothing of 42 parameters of cervical vertebrae and SMI.

Table III. Correlations between the 42 parameters of cervical vertebrae and SMI

Correlation	*Parameters*
Positive	D2, D3, D4, @2, @3, @4, PH3, H3, AH3, AD3, PD3, AH3/H3, H3/PH3, AH3/PH3, AH3/W3, H3/W3, PH3/W3, AD3/PD3, PH4, H4, AH4, AD4, PD4, AH4/H4, H4/PH4, AH4/PH4, AH4/W4, H4/W4, PH4/W4, AD4/PD4
Negative	AI2-3, PI2-3, AI3-4, PI3-4
Zero	UW3, W3, LW3, UW3/LW3, UW4, W4, LW4, UW4/LW4

Table IV. Correlation coefficient (CC) between the 34 correlated parameters and SMI

Parameter	*CC*	*Parameter*	*CC*	*Parameter*	*CC*
H4/W4	0.9107	AH3/W3	0.8828	PH4/W4	0.7875
H3/W3	0.9091	AD4/PD4	0.8748	PH3/W3	0.7653
H3	0.9024	@2	0.8617	AH4/H4	0.693
AH3	0.8992	D2	0.8503	AH3/H3	0.6697
AH3/PH3	0.8978	@3	0.8457	H4/PH4	0.5709
AD3	0.8974	D3	0.8302	H3/PH3	0.5414
AH4/PH4	0.8944	PH3	0.8258	PI3-4	–0.4363
AD3/PD3	0.8921	PH4	0.8221	PI2-3	–0.5073
H4	0.8907	PD3	0.8208	AI3-4	–0.6378
AH4	0.8901	PD4	0.8081	AI2-3	–0.658
AH4/W4	0.8892	D4	0.8008		
AD4	0.8859	@4	0.7941		

Table V. Variable cluster analysis of 10 parameters

Category	
I	H4/W4, H3/W3, AH4/W4, AH3/W3
II	AH3/PH3, AH4/PH4, AD3/PD3, AD4/PD4
III	@2, D2

Table VI. Value of variables from QCVM I to QCVM IV

	Variables		
QCVM	*H4/W4 (%)*	*AH3/PH3 (%)*	*@2 (°)*
I	0.63 ± 0.07	0.72 ± 0.05	7.17 ± 3.03
II	0.74 ± 0.06	0.80 ± 0.04	12.65 ± 3.26
III	0.84 ± 0.05	0.85 ± 0.03	15.63 ± 3.24
IV	0.98 ± 0.07	0.98 ± 0.06	20.81 ± 3.35

variable cluster analysis, 3 characteristic parameters (H4/W4, AH3/PH3, @2) were selected as the decisive measurement parameters for classification of CVM. This new method would be more simple and accurate to use than considering all parameters. The influence of subjectivity in QCVM was limited through quantification and simplification of parameters.

Figure 4 shows a patient's LCR and hand-wrist film. The hand-wrist film showed that the patient's

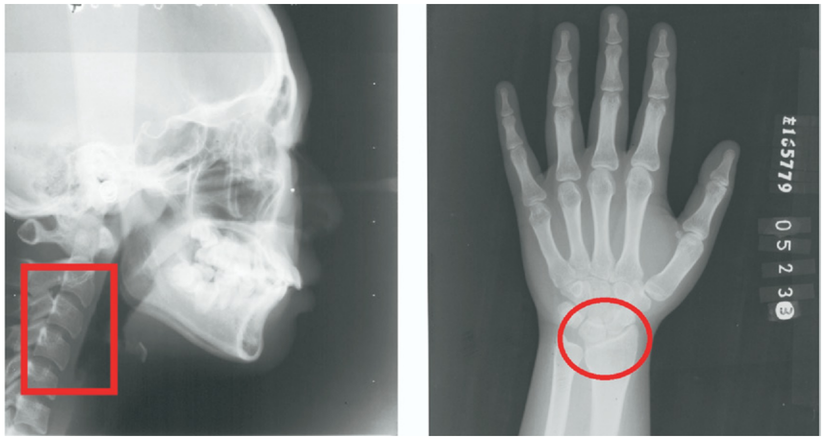

Fig 4. Headfilm and hand-wrist film of a subject. CVM indicated cervical vertebral bone age was CVM 4, just after the high-velocity period. However, QCVM indicated the patient belonged to QCVM IV, and the hand-wrist film indicated that the skeletal age was SMI 11, or the completed stage of growth.

skeletal age was SMI 11—ie, the completed stage of growth. QCVM showed that H4/W4 was 0.87, AH3/PH3 was 1.01, @2 was 21.32, and CVMS was 3.73, belonging to QCVM IV and agreeing with the hand-wrist skeletal age. However, CVM showed that the patient's cervical vertebral bone age was CVM 4, just after the high-velocity period, because there was conspicuous concavity in all vertebrae, and the shape of the vertebral bodies was rectangular. This disagreed with the completed stage of growth as shown by hand-wrist film.

Morphologic characteristic parameters of CVM were concavity of the lower border, and height and shape of the vertebral bodies. Three decisive variables (H4/W4, AH3/PH3, and @2) of QCVM selected from the 42 parameters were similar to those of CVM but more definite. Using only C2 through C4 and 3 more sensitive parameters to perform the staging can simplify the assessment process.

Cephalometric landmarks of the cervical vertebrae were easy to identify and measure by using cephalometric analysis software. A quantitative definition of the cervical vertebral morphology at each development stage allowed clinicians to accurately estimate the maturation stage from 1 cephalogram. The assessment of the stages in CVM through the comparative analysis of between-stage changes should be avoided; this in turn would improve the accuracy and repeatability.

In QCVM, comprehensive means and standard deviations of the CVMS could be worked out through the means and standard deviations of the 3 key variables. Moreover, the main contribution of this study was that, with the 3 morphologic variables, an equation that can accurately estimate the maturation of the cervical vertebrae was established: $CVMS = -4.13 + 3.57 \times H4/W4 + 4.07 \times AH3/PH3 + 0.03 \times @2$. This equation made QCVM more practical.

CONCLUSIONS

With LOESS smoothing, CC analysis, and variable-cluster analysis of the mixed longitudinal data from 8 to 18 years of age, a quantitative analysis for the cervical vertebrae was established. The conclusions were as follows.

1. H4/W4, AH3/PH3, and @2 can be used as the decisive parameters of the quantitative analysis.
2. QCVM was divided into 4 stages: QCVM I, QCVM II, QCVM III, and QCVM IV, which are adequate for the assessment of skeletal maturation. Every stage has its definitive quantitative standard.
3. An equation to accurately estimate CVM was established: $CVMS = -4.13 + 3.57 \times H4/W4 + 4.07 \times AH3/PH3 + 0.03 \times @2$. The definition of each stage was in QCVM I, $CVMS < 1.7404$; in QCVM II, $1.7404 < CVMS < 2.623$; in QCVM III, $2.623 < CVMS < 3.5199$; and in QCVM IV, $CVMS > 3.5199$.

The method of QCVM is an efficient, objective, and relatively simple approach to assess skeletal maturation during adolescence. It has a bright future in clinical orthodontics.

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