Original Article

Responsiveness of three measurements in cone-beam computed tomography transverse analyses during both tooth-supported and mini-screw-assisted rapid maxillary expansion

Lin Kong[a]; Yao Liu[a]; Xincan Zhou[a]; Hong He[b]; Zhijian Liu[c]

ABSTRACT

Objective: To evaluate the responsiveness of three cone-beam computed tomography (CBCT) transverse analyses (University of the Pennsylvania [UPenn] analysis, Boston University analysis and Yonsei University [YU] analysis).

Materials and Methods: A consecutive cohort sample of patients was retrospectively reviewed for eligibility. CBCT records before treatment (T0) and immediately after maxillary expansion (T1) of 71 patients receiving tooth-supported rapid maxillary expansion (RME) and 57 patients receiving mini-screw-assisted RME (MARME) were finally analyzed. Responsiveness was assessed by comparing changes of measures (T1-T0) to mid-palatal suture opening distance (MSOD) at T1. Correlational responsiveness was assessed by Pearson correlation coefficient (r). Absolute agreement responsiveness was assessed by Bland-Altman analysis. A specialized intraclass correlation coefficient (ICC) was selected to assess responsiveness combining correlation and absolute agreement.

Results: Changes of all three measures were moderately to strongly correlated to MSOD ($r > 0.5$). The highest correlation coefficient (0.79) was found between the YU analysis and MSOD. When exploring absolute agreement responsiveness, the smallest deviation (0.14 mm) was observed in the UPenn analysis. For ICC, the highest ICC value (0.63) was observed when the YU analysis was used. In addition, all three measurements were more responsive to MSOD in the MARME group than to those in RME group.

Conclusions: All three transverse measurements responded well to true changes of maxillary transverse deficiency during both tooth-supported and mini-screw-assisted RME. Deviations of responsive properties of these measurements from true skeletal changes were below a clinically meaningful level (1 mm). (*Angle Orthod*. 2024;94:39–50.)

KEY WORDS: CBCT transverse analysis; Responsiveness; Validity

INTRODUCTION

Skeletal maxillary transverse deficiency (MTD) is one of the most common orthodontic problems, characterized by narrowed maxillary dentition, upper arch crowding, unilateral or bilateral posterior crossbite, and excess buccal corridor space.[1] MTD may not only cause periodontal

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damage and muscular dysfunction but also may be associated with anterior-posterior jaw discrepancy and facial asymmetry.[2] Therefore, it is of fundamental importance to properly diagnose MTD and address it adequately during orthodontic treatment planning.

Numerous methods and measurements have been proposed for diagnosing skeletal transverse problems.[3,4] However, most of them were developed for dental casts or traditional two-dimensional (2D) posterior-anterior (P-A) cephalogram analysis with considerable limitations in reliability and validity.[5] The widespread use of cone-beam computed tomography (CBCT) in orthodontic diagnosis sheds some new light on this classic topic. Aiming to diagnose the skeletal transverse discrepancy between the maxilla and mandible, three CBCT-based transverse analyses have been developed recently and published: the University of the Pennsylvania (UPenn) CBCT transverse analysis,[6] Boston University (BU) CBCT transverse analysis,[7] and Yonsei University (YU) CBCT transverse analysis.[8] Although the reliability of these transverse measurements has already been shown by previous studies,[7–9] the validity of these measurements remains uncertain, especially when using them to justify the necessity for maxillary mid-palatal suture expansion and to determine the desired amount of palatal suture expansion.

Responsiveness, sometimes referred to as responsive validity,[10,11] pertains to the ability of a measurement to properly respond to changes in the construct(s) it purports to measure. As proposed by the Consensus-Based Standards for the Selection of Health Measurement Instruments panel, responsiveness is one of the three essential clinimetric properties reflecting the quality of medical and health measurements, although it is still controversial whether it is a part of validity or it is an independent measurement property different from validity and reliability.[12] Theoretically, a measurement is responsive if its value changes when there are known changes in what it purports to measure. An acceptable measurement for determining skeletal transverse discrepancy should properly respond to the changes of skeletal transverse relationships between the maxilla and mandible. Therefore, changes of skeletal transverse measurement values should respond to mid-palatal suture opening distance (MSOD) in a valid way, reflecting true changes in skeletal transverse dimensions. First, there should be sufficient correlation between changes of measurement values and MSOD after expansion. Furtherly, changes of measurements should respond well to MSOD in a manner of absolute agreement, ideally as a 1:1 ratio.

The aim of this study was to assess the responsiveness of three previously published skeletal transverse measurements by assessing the correlation and absolute agreement between the changes of these measurements and MSOD immediately after maxillary expansion in both tooth-supported rapid maxillary expansion (RME) and mini-screw-assisted RME (MARME) groups. The knowledge generated from this study was expected to provide insight into the measurement properties of current orthodontic transverse analyses on CBCT. The null hypothesis was that changes of these three measurements would not properly respond to the change of MTD; the correlation or absolute agreement between them would be low. The true hypothesis was that changes of these three measurements would respond properly to the change of MTD in both correlation and absolute agreement manners.

MATERIALS AND METHODS

This study was approved by the institutional review board of the School & Hospital of Stomatology, Wuhan University, China (number 2022-B01). Because this retrospective study was based on currently available clinical data, the institutional review board waived patient informed consent requirements. A consecutive sample of patients receiving orthodontic treatment between September 2013 and October 2022 at the Department of Orthodontics, School & Hospital of Stomatology, Wuhan University was screened for eligibility. The inclusion criteria were (1) patients receiving RME or MARME, (2) patients with all four upper and lower first molars present, and (3) available CBCT images before treatment (T0) and immediately after expansion (T1). The exclusion criteria were (1) patients with craniofacial deformities, such as cleft lip and palate; (2) patients undergoing surgically assisted RME; and (3) patients having other orthopedic treatment, for example, maxillary protraction or bite jumping, along with maxillary expansion.

In the RME group, a modified type of bonded Haas expander (Shinye, Hangzhou, China) with acrylic occlusal splints and two acrylic palatal pads was used (Figure 1A). In the MARME group, the maxillary skeletal expander (MSE, type-II; BioMaterials Korea Inc, Seoul, Korea), with two orthodontic molar bands, four insertion slots, and a jackscrew unit was used (Figure 1B). The Haas expander was activated two turns per day (0.5 mm per day), and the MSE was activated three turns per day (0.5 mm per day), for an average time of 17 days (range, 14–21 days).

CBCT images at T0 were the initial orthodontic records of all patients. CBCT images at T1 were acquired on the day of the completion of expansion. The average interval between T0 and T1 was 42 days, with the smallest interval being 38 days (range, 38–46 days), consisting of the time of expander production and active expansion. CBCT images at T0 and T1 were all taken using the NewTom VG (QR srl, Verona, Italy) with a 15 $\times$ 15 cm field of view, 0.3 mm voxel size, and 3.6 seconds of exposure time, for which the effective dose was about

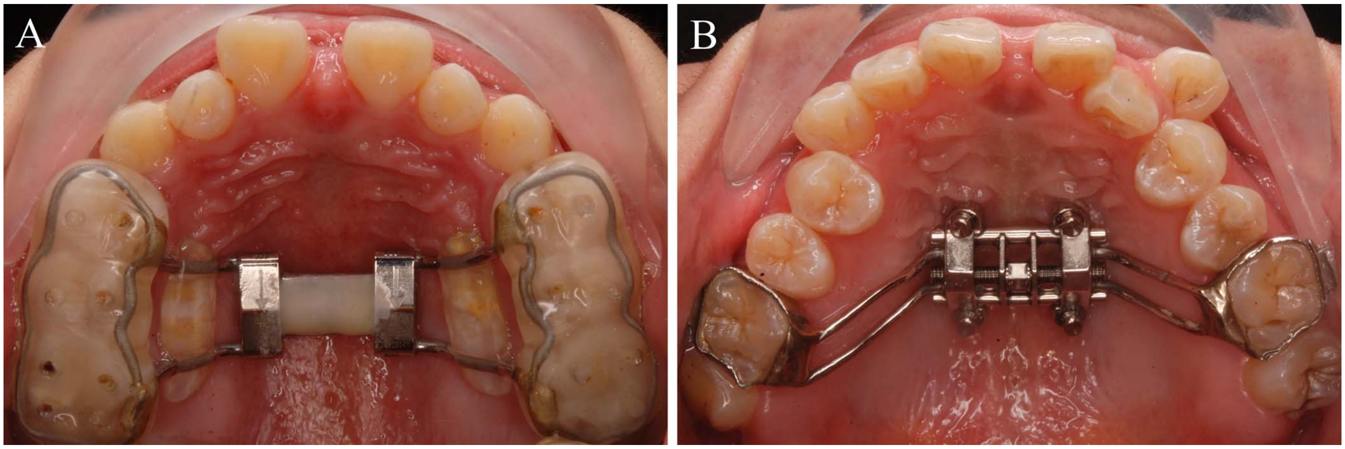

Figure 1. (A) Bonded Haas expander. (B) Maxillary skeletal expander.

83 μSv.[13] All the CBCT practices were conducted under the guidelines of the use of CBCT in dentistry to minimize patient exposure.[14,15]

CBCT Orientation and Skeletal Transverse Measurements on CBCT

Eligible patient CBCT records were first imported to Dolphin Imaging software version 11.95 (Dolphin Imaging and Management Solutions, Chatsworth, Calif). Then, the three-dimensional (3D) orientation of CBCT images was adjusted for each measurement according to previous protocols (Table 1 and Figure 2).[6–8] For the measurement of MSOD, the axial plane was reoriented to parallel a line connecting anterior nasal spine (ANS) and posterior nasal spine (PNS) (Figure 2C).

Measurements of three CBCT transverse analyses at T0 and T1 and MSOD at T1 were measured for each patient as previously reported (Figures 3–6).[6–8] The definitions of landmarks and parameters assessed in this study are summarized in Table 2. The CBCT data of all patients were coded and assigned blindly to two calibrated examiners (Dr Liu and Dr Zhou). A total of 10 patients (8% of the sample) were randomly selected for remeasurement.

Statistical Analysis

Sample size calculation was performed using PASS software, version 15.0 (NCSS Statistical Software, Kaysville, U.T.). For a minimum acceptable reliability (intraclass correlation coefficient [ICC]) of 0.6 and an expected reliability of 0.8, with α at 0.05 and β at 0.2, at least 39 patients in each group were needed.

The normality of data distribution was assessed by the Shapiro-Wilk test. The intrarater and interrater reliability were assessed by ICC, considering $P < .05$ as statistically significant.

The correlational responsiveness was assessed by Pearson correlation coefficient (r). The correlation was considered as strong when $r \geq 0.75$, moderate when $0.50 < r < 0.75$, low when $0.25 < r < 0.50$, and none when $r \leq 0.25$.[16]

The absolute agreement responsiveness was assessed by Bland-Altman analysis. Because MSOD was the true change of MTD, it was plotted as the *x*-axis of the Bland-Altman plots.[17] The deviation (referred to as bias in Bland and Altman[18]) between measure changes and MSOD was plotted as the *y*-axis. The ideal responsiveness was defined as the *y*-axis sufficiently close to zero with a small range of limits of agreement (LOA).[18]

The combined correlational and agreement responsiveness was assessed by ICC in the form of two-way mixed effects, absolute agreement, and single measurement.

Table 1. CBCT Orientation for the Measurement of Three CBCT Transverse Analyses[a]

	Axial Plane	Coronal Plane	Mid-Sagittal Plane
UPenn analysis and YU analysis	Frankfort horizontal plane	Pass through the floor of both orbits, perpendicular to the axial plane	Pass through the midpoint between inner rims of two orbits, perpendicular to both the axial and coronal planes
BU analysis	Functional occlusal plane	Pass through the buccal groove of the right maxillary first molar, perpendicular to the axial plane	The same as in the measurement of UPenn analysis and YU analysis

[a] BU indicates Boston University; CBCT, cone-beam computed tomography; UPenn, University of the Pennsylvania; and YU, Yonsei University.

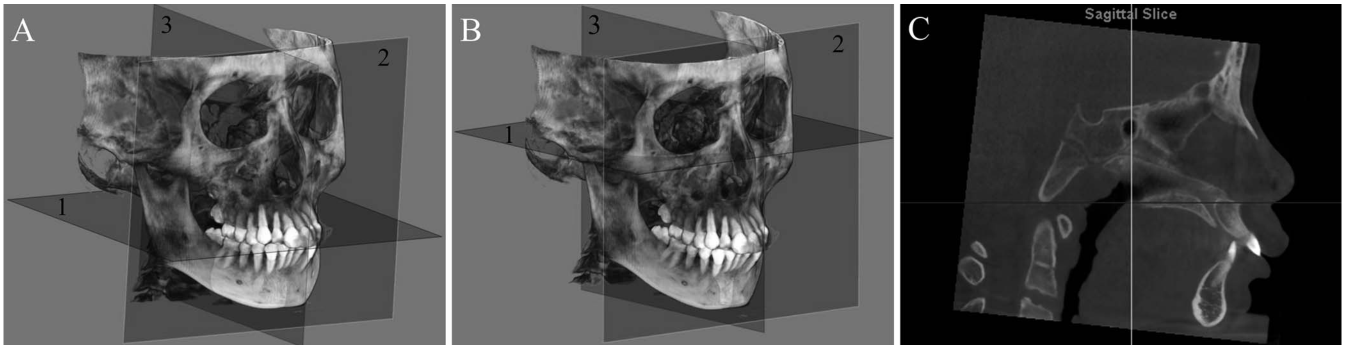

Figure 2. (A) Cone-beam computed tomography (CBCT) orientation for measurement of the Boston University analysis. Plane 1: functional occlusal plane. Plane 2: coronal plane. Plane 3: mid-sagittal plane. (B) CBCT orientation for measurements of the University of the Pennsylvania and Yonsei University analyses. Plane 1: Frankfort plane. Plane 2: coronal plane. Plane 3: mid-sagittal plane. (C) Reorientation of axial plane for measurement of the mid-palatal suture opening distance.

Figure 3. Transverse measurement of the University of the Pennsylvania (UPenn) analysis.

Figure 4. Transverse measurement of the Boston University (BU) analysis.

An ICC was classified as almost perfect, substantial, moderate, fair, and poor to slight when the value was in the range 0.81 to 1.00, 0.61 to 0.80, 0.41 to 0.60, 0.21 to 0.40, and below 0.20, respectively.[19] All statistical analyses were performed with SPSS software version 26.0 (IBM Corp, Armonk, N.Y.) and MedCalc Software (Ostend, Belgium) version 20.0.22.

RESULTS

A total of 128 patients (36 males, 92 females), with a mean age of 13.6 ± 3.6 years were enrolled retrospectively in this study. The RME group consisted of 71 patients (20 males, 51 females), with a mean age of 11.8 ± 0.9 years. The MARME group consisted of 57 patients (16 males, 41 females), with a mean age of 15.8 ± 4.4 years. The data distribution of changes of the three measures and MSOD as well as the difference between them did not show significant violation to the basic assumption for the parametric inferential test.

Reliability

The ICC values of all the skeletal measurements were above 0.8, varying from 0.89 to 0.98, which indicated almost perfect intrarater and interrater reliability (Table 3).

Responsiveness of Three Measurements of CBCT Transverse Analyses

With regard to correlational responsiveness, there were moderate to strong positive correlations between changes of all three transverse measurements and MSOD. The YU analysis had the highest correlation coefficients in the entire group of patients (0.79), RME

Figure 5. Transverse measurement of the Yonsei University (YU) analysis.

group (0.70), and MARME group (0.91). The lowest correlation coefficients were found in the UPenn analysis for the entire group of patients (0.59) and the MARME group (0.64). In addition, the correlation coefficients of the three measurements were all higher in the MARME group than in the RME group (Table 4).

For absolute agreement responsiveness, the mean deviations between changes of the three transverse measurements and MSOD were all lower than 1.03 mm. The UPenn analysis showed the smallest deviation in the entire group of patients and two subgroups, and the change of measure in the UPenn analysis tended to equally estimate MSOD ($P \geq .05$). However, the properties of the UPenn analysis were accompanied by the widest LOA. The YU analysis had the largest deviation, and the change of measure in the YU analysis tended to overestimate MSOD ($P < .05$). Nevertheless, the narrowest LOA was observed in the YU analysis. A moderate deviation and moderate LOA were observed in the BU analysis. Similar to the YU analysis, change of measure in the BU analysis tended to overestimate MSOD. In addition, the deviations and LOA of the three measurements in the MARME group were all lower than those in the RME group (Table 5 and Figures 7–9).

When exploring the combined correlational and absolute agreement responsiveness, the results of the ICC were similar to correlational responsiveness. The highest ICC values were found in the YU analysis for the entire group of patients (0.63), RME group (0.45), and MARME group (0.82). The lowest ICC values were observed in the UPenn analysis for the entire group of patients (0.54) and MARME group (0.62).

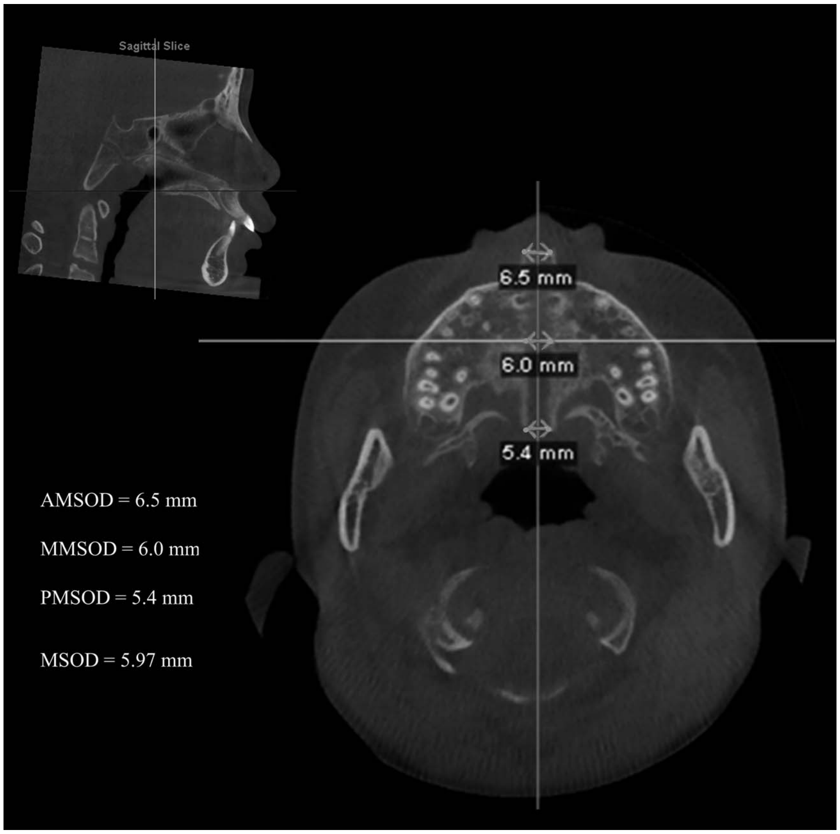

Figure 6. Linear measurement of MSOD. AMSOD indicates anterior mid-palatal suture opening distance; MMSOD, middle mid-palatal suture opening distance; MSOD, mid-palatal suture opening distance; and PMSOD, posterior mid-palatal suture opening distance.

Table 2. Definitions of Landmarks and Parameters Assessed in This Study[a]

Landmark/Parameter	Definition
Maxillary landmark of UPenn analysis	The intersection point of the cut line with the cortical plate on axial slice while the cut line passes through Mx-Mx (the junction of the maxilla and zygomatic buttress) on coronal slice.[6]
Mandibular landmark of UPenn analysis	The intersection point of the cut line with the cortical plate on axial slice while the cut line passes through the furcation of mandibular first molars on coronal slice.[6]
Maxillary landmark of BU analysis	The alveolar point on the palatal cortex opposite the midpoint of buccal alveolar crest and buccal root apex of maxillary first molar.[7]
Mandibular landmark of BU analysis	The alveolar point on the lingual cortex opposite the midpoint of buccal alveolar crest and apex of mandibular first molar.[7]
Maxillary landmark of YU analysis	The center point of maxillary first molar's roots on axial slice where the coronal slice intersected the furcation of maxillary first molars. The furcation of maxillary first molars was confirmed on coronal, sagittal, and axial views.[8]
Mandibular landmark of YU analysis	The center point of mandibular first molar's roots on axial slice where the coronal slice intersected the furcation of mandibular first molars. The furcation of mandibular first molars was confirmed on coronal, sagittal, and axial views.[8]
Maxillary width	Linear distance between two maxillary landmarks.
Mandibular width	Linear distance between two mandibular landmarks.
Transverse measurement in CBCT transverse analysis	The difference between maxillary width and mandibular width.
Anterior mid-palatal suture opening distance (AMSOD)	Linear distance between ANS points on two halves of the palate on axial slice.
Middle mid-palatal suture opening distance (MMSOD)	Linear distance between the midpoints of ANS and PNS on two halves of the palate on axial slice.
Posterior mid-palatal suture opening distance (PMSOD)	Linear distance between PNS points on two halves of the palate on axial slice.
Mid-palatal suture opening distance (MSOD)	The average of AMSOD, MMSOD, and PMSOD.

[a] ANS indicates anterior nasal spine; BU, Boston University; CBCT, cone-beam computed tomography; PNS, posterior nasal spine; UPenn, University of the Pennsylvania; and YU, Yonsei University.

Table 3. Intrarater and Interrater Reliability of All the Skeletal Measurements[a]

	UPenn Analysis ICC (95% CI)		BU Analysis ICC (95% CI)		YU Analysis ICC (95% CI)		MSOD ICC (95% CI)		
	Maxillary Width	Mandibular Width	Maxillary Width	Mandibular Width	Maxillary Width	Mandibular Width	AMSOD	MMSOD	PMSOD
Intrarater reliability (Dr Liu)	0.98 (0.94–0.99)	0.97 (0.92–0.99)	0.98 (0.94–0.99)	0.95 (0.89–0.98)	0.97 (0.92–0.99)	0.97 (0.92–0.99)	0.97 (0.89–0.99)	0.97 (0.88–0.99)	0.94 (0.77–0.98)
Intrarater reliability (Dr Zhou)	0.96 (0.81–0.99)	0.95 (0.89–0.98)	0.97 (0.93–0.99)	0.96 (0.90–0.98)	0.95 (0.87–0.98)	0.92 (0.81–0.97)	0.97 (0.89–0.99)	0.95 (0.81–0.99)	0.94 (0.78–0.99)
Interrater reliability	0.96 (0.91–0.99)	0.94 (0.51–0.98)	0.91 (0.75–0.97)	0.97 (0.92–0.99)	0.94 (0.83–0.98)	0.97 (0.91–0.99)	0.97 (0.88–0.99)	0.95 (0.83–0.99)	0.89 (0.61–0.97)

[a] AMSOD indicates anterior mid-palatal suture opening distance; BU, Boston University; CBCT, cone-beam computed tomography; CI, confidence interval; ICC, intraclass correlation coefficient; MMSOD, middle mid-palatal suture opening distance; MSOD, mid-palatal suture opening distance; PMSOD, posterior mid-palatal suture opening distance; UPenn, University of the Pennsylvania; and YU, Yonsei University.

The ICC values of the three measurements in the MARME group were all higher than those in the RME group (Table 6).

DISCUSSION

Increasing scientific evidence supports that the use of CBCT improves the performance of diagnosis, treatment planning, and outcome assessment in orthodontic practice.[20] Among these improvements, using CBCT as a diagnostic and treatment planning tool for MTD might be one of the most important developments. Many attempts have been made to quantify the pretreatment skeletal discrepancy and related dental compensations on CBCT for transverse diagnosis and treatment planning in a more measurable way.[6–8,21] Compared with traditional 2D P-A cephalograms and study cast analyses, skeletal transverse analyses on CBCTs are more reliable.[9] However, the validity of these measurements still needs to be confirmed further. The current study evaluating the responsiveness (responsive validity) of the three measurements in CBCT transverse analyses was designed to improve the understanding in the measurement properties of these analyses.

According to the results of the Pearson correlation analysis, the YU analysis showed the highest correlational responsiveness. However, correlation only describes the strength of the linear relationship between two variables, but not the amount of absolute agreement.[18] Therefore, it could be concluded that the YU analysis was the most sensitive to reflect changes of MTD proportionately. However, this did not necessarily imply that the YU analysis was valid in reflecting changes of MTD in a manner of absolute agreement. Results of the Bland-Altman analysis, considering both the amount of deviation from the true value and LOA, suggested that the UPenn analysis and the YU analysis were more responsive to true changes of MTD than the BU analysis in the manner of absolute agreement. In addition, the range of LOA of the UPenn analysis was relatively wider than the YU analysis. This wider range in absolute agreement responsiveness may have been attributed to the greater variation in maxillary and zygomatic buttress anatomy, which are highly related to the stability of UPenn landmarks. In addition, the position and shape of the maxillary sinus may also affect UPenn landmark identification. Although there were slight differences in absolute agreement responsiveness among these measurements, most of the deviations from true skeletal changes were below a clinically meaningful level (1 mm). Regarding the results of ICC, which considered both correlational and absolute agreement responsiveness, the scores of all three measurements were higher than 0.4, suggesting acceptable responsiveness.

Table 4. Correlational Responsiveness of Three CBCT Transverse Measurements by Pearson Correlation Coefficient[a]

	UPenn Analysis		BU Analysis		YU Analysis	
	r	*P* Value	*r*	*P* Value	*r*	*P* Value
All patients	0.59	$<.001$	0.63	$<.001$	0.79	$<.001$
RME group	0.57	$<.001$	0.57	$<.001$	0.70	$<.001$
MARME group	0.64	$<.001$	0.74	$<.001$	0.91	$<.001$

[a] BU indicates Boston University; CBCT, cone-beam computed tomography; MARME, mini-screw-assisted rapid maxillary expansion; RME, rapid maxillary expansion; UPenn, University of the Pennsylvania; and YU, Yonsei University.

Based on the results of these three methods for evaluating responsiveness in both correlation and absolute agreement terms, the null hypothesis of this study was rejected. In general, all three transverse measurements were responsive to the true value of changes they intended to measure. Possible deviations of using these measurements to detect true changes of MTD were not significant at a clinically meaningful level (1 mm).

Another interesting finding from this study was that the responsive properties of all these measurements

Table 5. Deviations (mm) Between Changes of Measures and MSOD (mm)[a]

	MSOD	Deviation of UPenn Analysis			Deviation of BU Analysis			Deviation of YU Analysis		
	Mean ± SD	Mean ± SD	LOA	*P* Value	Mean ± SD	LOA	*P* Value	Mean ± SD	LOA	*P* Value
All patients	3.32 ± 1.14	0.14 ± 1.42	−2.64 to 2.92	.26	0.57 ± 1.22	−1.81 to 2.96	<.001	0.88 ± 0.96	−1.00 to 2.76	<.001
RME group	3.11 ± 0.88	0.33 ± 1.44	−2.49 to 3.16	.05	0.78 ± 1.31	−1.79 to 3.36	<.001	1.03 ± 1.13	−1.18 to 3.24	<.001
MARME group	3.59 ± 1.36	−0.09 ± 1.37	−2.77 to 2.58	.60	0.31 ± 1.04	−1.73 to 2.35	.03	0.69 ± 0.65	−0.59 to 1.97	<.001

[a] BU indicates Boston University; LOA, limits of agreement; MARME, mini-screw-assisted rapid maxillary expansion; MSOD, mid-palatal suture opening distance; RME, rapid maxillary expansion; UPenn, University of the Pennsylvania; SD, standard deviation; and YU, Yonsei University.

were better in the MARME group than in the RME group. Previous studies confirmed that dental and alveolar tipping were unavoidable during maxillary expansion even when MARME was used.[2] There were far more significant dental and alveolar tipping effects in the RME group than in the MARME group.[22] Better responsiveness in the MARME group of the current study was probably attributed to the lesser amount of dental and alveolar tipping that occurred when mini-screws were used to assist maxillary expansion. Therefore, the difference in responsiveness between the RME and MARME groups was supportive evidence that these transverse measurements seemed to be more specific to skeletal changes than dentoalveolar changes. Because both the design of maxillary expanders and the age of patients have an impact on the effectiveness of maxillary expansion, how responsive these measurements are after expansion is probably affected by both of these factors. In addition, different skeletal expansion patterns may also contribute to the different responsive performances of these measurements in two subgroups, as all three of these measurements are made in the posterior region of the maxilla. RME was reported to produce a triangular skeletal expansion pattern with more expansion in the anterior region, whereas the expansion pattern was rather parallel in MARME group.[22] The long-term responsiveness of transverse measurements was not assessed in this study because MSOD would be very hard to measure with an ossified suture that would be expected in the retention phase.

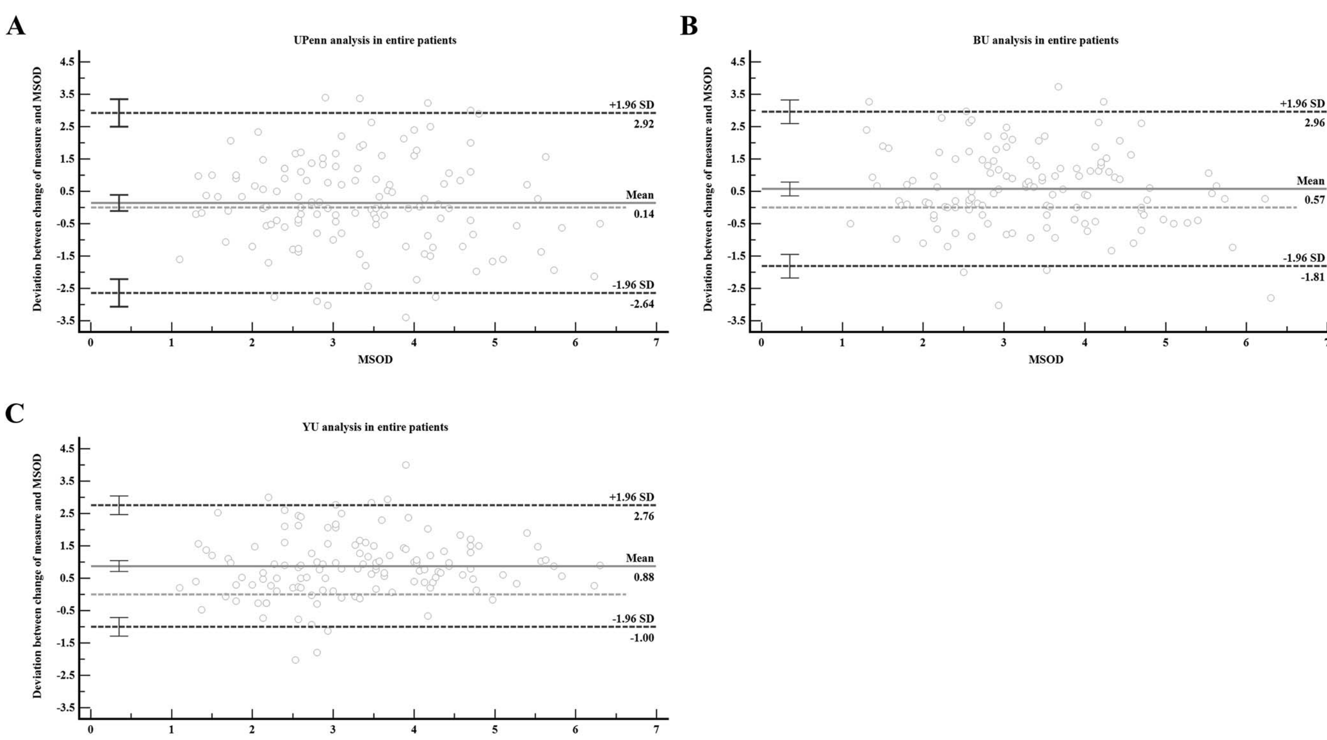

Figure 7. Absolute agreement responsiveness of three measurements in the entire group of patients. (A) UPenn analysis. (B) BU analysis. (C) YU analysis. BU indicates Boston University; MSOD, mid-palatal suture opening distance; UPenn, University of the Pennsylvania; and YU, Yonsei University.

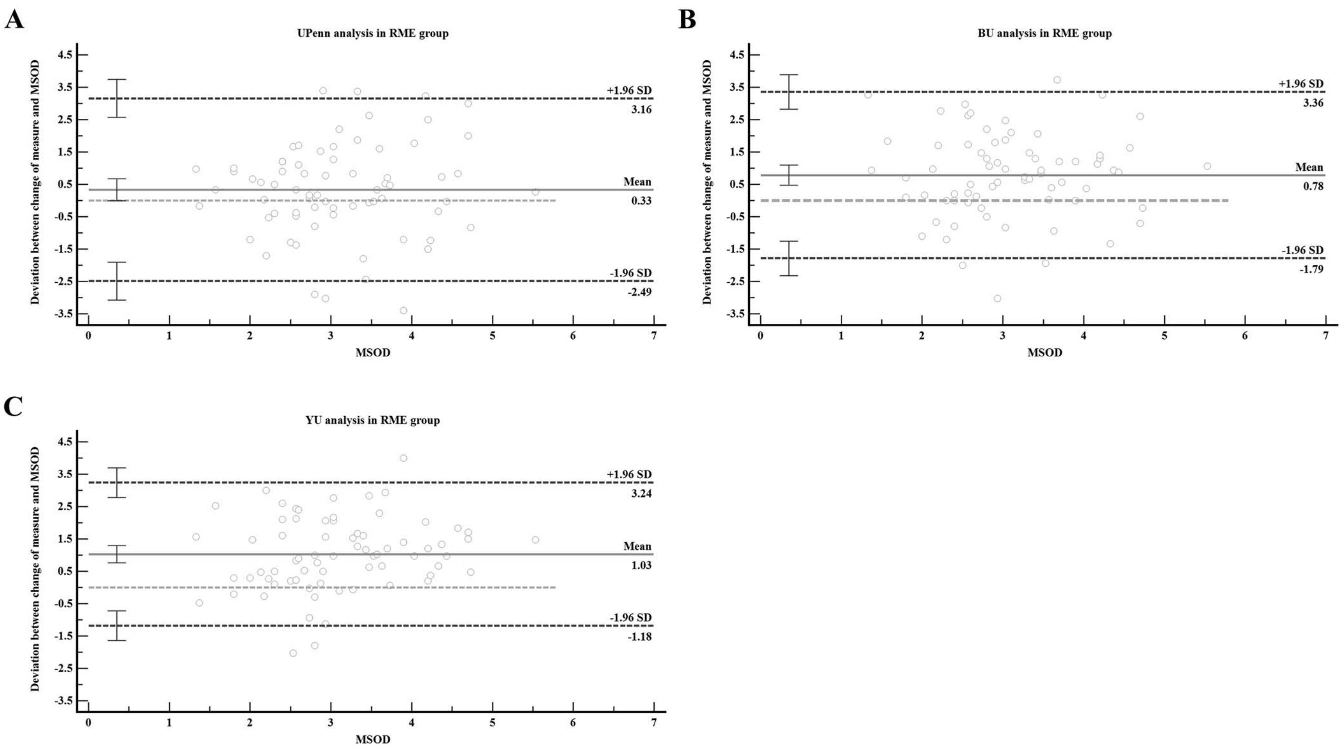

Figure 8. Absolute agreement responsiveness of three measurements in the RME group. (A) UPenn analysis. (B) BU analysis. (C) YU analysis. BU indicates Boston University; MSOD, mid-palatal suture opening distance; RME, rapid maxillary expansion; UPenn, University of the Pennsylvania; and YU, Yonsei University.

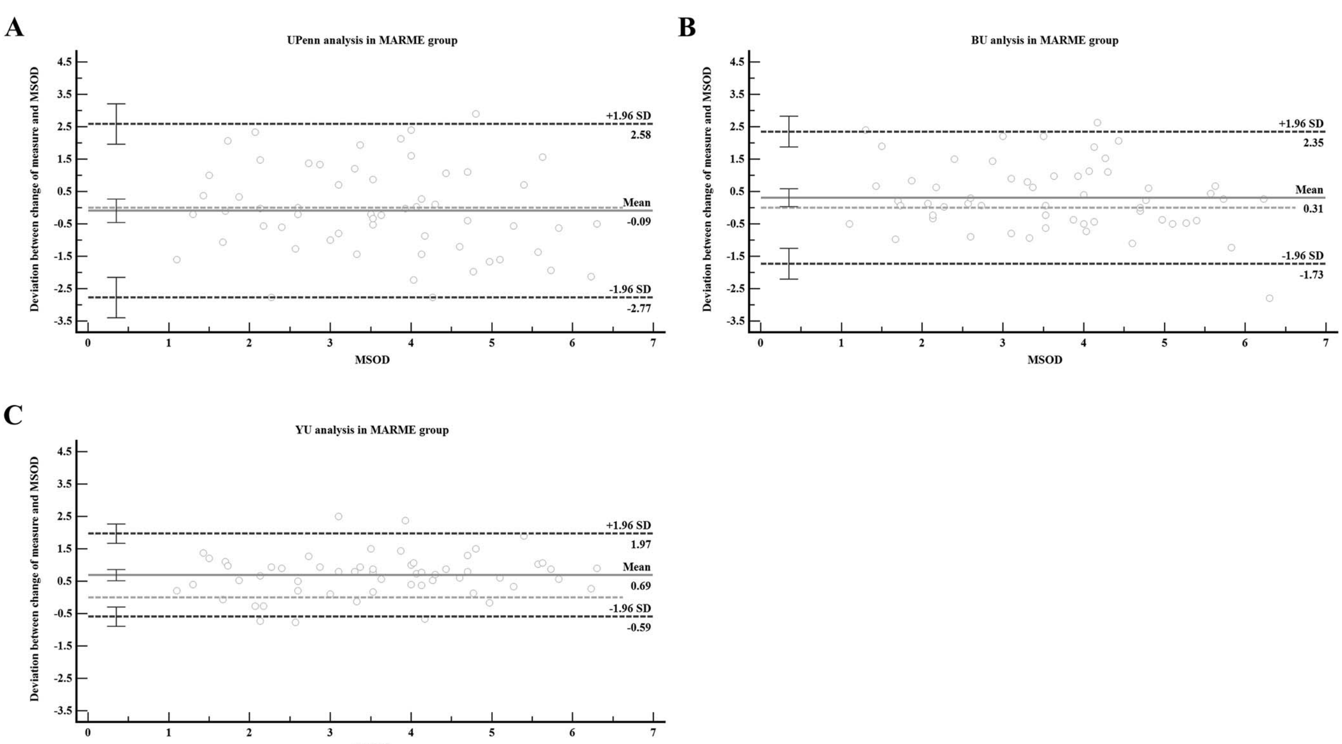

Figure 9. Absolute agreement responsiveness of three measurements in the MARME group. (A) UPenn analysis. (B) BU analysis. (C) YU analysis. BU indicates Boston University; MARME, mini-screw-assisted rapid maxillary expansion; MSOD, mid-palatal suture opening distance; UPenn, University of the Pennsylvania; and YU, Yonsei University.

Table 6. ICC Values of Three CBCT Transverse Measurements[a]

	UPenn Analysis		BU Analysis		YU Analysis	
	ICC	95% CI	ICC	95% CI	ICC	95% CI
All patients	0.54	0.40–0.65	0.55	0.36–0.69	0.63	0.13–0.82
RME group	0.45	0.25–0.62	0.41	0.13–0.61	0.45	0.02–0.70
MARME group	0.62	0.43–0.76	0.73	0.57–0.83	0.82	0.23–0.93

[a] BU indicates Boston University; CBCT, cone-beam computed tomography; CI, confidence interval; ICC, intraclass correlation coefficient; MARME, mini-screw-assisted rapid maxillary expansion; RME, rapid maxillary expansion; UPenn, University of the Pennsylvania; and YU, Yonsei University.

Although this study was carefully designed, there were still some limitations. First, further properly designed diagnostic studies and clinical trials are still needed to confirm other aspects of the validity of these transverse measurements. Second, to reflect opening distance of the whole mid-palatal suture, the value of MSOD in this study was obtained by calculating the average values of the anterior mid-palatal suture opening distance, middle mid-palatal suture opening distance, and posterior mid-palatal suture opening distance at the ANS-PNS level. However, there might be variations of opening distance at different sites of the palatal suture.[23] With the continuing development of 3D superimposition techniques, this issue may be better managed in the future.

CONCLUSIONS

- All three transverse measurements studied responded well to the true change of MTD during both tooth-supported RME and MARME.
- The YU analysis showed relatively higher responsiveness in both a correlational manner and the manner combining correlation and absolute agreement together.
- Compared with the BU analysis, the UPenn analysis and YU analysis were better in absolute agreement responsiveness.
- Deviations of responsive properties of all the measurements from true skeletal changes were below a clinically meaningful level (1 mm).

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