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Bone Modifications Induced by Rapid Maxillary Expander: A Three-Dimensional Cephalometric Pilot Study Comparing Two Different Cephalometric Software Programs

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Abstract: Cone-beam computed tomography (CBCT) allows for more accurate 3D study of the craniofacial region and the development of a very precise treatment plan. The present pilot study aims to evaluate the skeletal outcomes of the rapid maxillary expander (RME) on the sagittal, transverse and vertical planes in growing patients subjected to CBCT at T0 and T1, and to compare the results from two different programs. The effects of the RME are monitored in 11 patients who were subjected to CBCT at T0, before the expansion, and at T1, 6 months after the end of the RME therapy. The results obtained are evaluated using two programs: Simplant and Delta-Dent. All of the analyses were performed by the same operator. Both programs reported statistically significant differences between the pre- and post-expansion values of the parameters on the transverse plane. On the vertical plane, only posterior facial height showed a statistically relevant variation. Both programs underlined a discrepancy between the pre- and post-expansion infraorbital and mental foramina distance values; however, this difference was considered statistically significant by Delta-Dent, and not by Simplant. CBCT is a reliable and effective tool for orthodontic diagnosis and treatment planning. Both of the evaluated programs are efficient in tridimensional cephalometric analysis.

Keywords: rapid maxillary expander (RME); cone-beam computed tomography (CBCT); cephalometric analysis; Simplant; Delta-Dent; dentistry; orthodontics

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1. Introduction

Cone-beam computed tomography (CBCT) represents important technological progress in the fields of tomographic acquisition and volumetric reconstruction [1]. The approach involves a significantly reduced radiant dose compared with traditional computed tomography (CT) and provides all of the radiological information required for a complete study of an orthodontic case [2,3]. CBCT has been increasingly performed in orthodontics to study 3D craniofacial anatomy in order to improve diagnosis and treatment planning, and to assess treatment outcomes [4]. This imaging technique can be useful to examine many pathological conditions, such as impacted and supernumerary teeth, cleft lip and palate, asymmetries, root resorption, obstructive sleep apnea (OSA), TMJ disorders and maxillary transverse deficiency [5].

A rapid maxillary expander (RME) is indicated in growing patients with maxillary width deficiency [6], as it applies orthopedic forces resulting in the widening and gradual opening of the midpalatal suture, compression of the periodontal ligament, bending of the alveolar processes and dental tipping [7]. As a result, the maxillary bones widen on the transverse plane, with the frontonasal suture as the approximate center of rotation [8].

Although the midpalatal suture is subjected to the majority of the effects of the RME, the surrounding frontomaxillary, zygomaticomaxillary, zygomaticotemporal and pterygopalatine sutures also experience some changes [9]. Sometimes, the RME can improve nasal breathing by widening the nasal cavities [10]. Different studies in the literature evaluated the craniofacial outcomes of RME therapy [11,12]. In the past, these effects were evaluated using lateral and posteroanterior cephalograms; however, CBCT now provides the opportunity to conduct a 3D analysis [11]. Radiography guidelines in the USA and Europe promote the "As Low As Reasonably Achievable" (ALARA) principle, especially when dealing with orthodontic patients who are mostly children, because of their attributable lifetime radiation risk [13,14]. If it is necessary to perform a CBCT, it must be executed using the smallest possible field of view [4]. According to systematic reviews [15,16], CBCT, and even 2D radiographs, which are generally taken routinely, should only be performed when they could offer more information useful for diagnosis or treatment planning or for evaluating progress or complications during the therapy. Two-dimensional cephalometric measurements are often inaccurate due to mistakes concerning landmark identification and projections [17], whereas 3D techniques allow these issues to be overcome thanks to the ability of dedicated programs to three-dimensionally rotate the image [18].

The rapid development of CBCT technology led to the introduction of various programs for orthodontists, with subsequent comparisons being made among them, as far as reliability and accuracy are concerned [19,20]. According to Farronato et al. [21], the 3D analysis provided by dedicated programs helps to avoid human error, reduces inter- and intra-individual variation and increases the reliability and repeatability of diagnoses. Burkhard and his colleagues [22] also reported the significant reliability of 3D cephalometric analysis performed by dedicated programs compared with the traditional manual technique. Many studies in the literature demonstrate how 3D software can provide a more reliable cephalometric analysis compared to the manual approach, obtaining more precise information that can improve diagnosis and treatment planning [23].

The programs available on the market are able to perform cephalometric analysis such as growth forecasts and treatment simulations. Some of these are capable of superimposing multiple cephalometric traces with pictures of the patient, also allowing the simulation of the effects of treatment on the soft tissues [24,25]. Three-dimensional software allows the orthodontist to perform virtual setups, treatment simulations and superimpositions of dental models with high reliability [26].

Many authors have recently investigated the numerous effects of RMEs with CBCT and various dedicated 3D software; for example, Bruder et al. evaluated the effects of RMEs, such as modifications of the depth of the palate and cross-sections of the maxilla, using CBCT and a related 3D software program [27].

Almuzian et al. were able to perform an accurate analysis of RMEs' outcomes on the upper airways thanks to CBCT and a specific 3D software program [28].

Fastuca et al. used CBCT and a specific 3D program to investigate a possible change to the condylar position after RME treatment [29].

In the literature, the use of CBCT and 3D software is also described as being utilized to assess root resorption as a consequence of RME treatment [30].

Therefore, the aim of the present pilot study is to compare 3D cephalometric analyses performed by two different programs, which evaluate the skeletal outcomes on the sagittal, transverse and vertical planes in growing patients subjected to a CBCT examination before orthopedic treatment with an RME (T0) and 6 months after the last RME activation (T1).

2. Materials and Methods

This pilot study was approved by the Unit Internal Review Board (2020-0205). Patients attending the Unit of Orthodontics and Pediatric Dentistry of the University of Pavia for orthodontic treatment were enrolled in the study, with written consent for performing CBCT being obtained from their parents [31]. The inclusion criteria were: patients with mono- or bilateral crossbite, need for Hyrax RME or Haas treatment, and indication for CBCT to evaluate the upper arch (maxillary displaced canines, presence of artifacts in the preliminary orthopantomography or other conditions that require CBCT for a complete diagnosis). The sample size calculation (alpha = 0.05; power = 95%) was performed considering "maxillary intermolar distance". The sample size calculation (alpha = 0.05; power = 80%) was performed considering "ANB angle" as a primary outcome. An expected mean of 4.16 with a standard deviation of 1.4 was hypothesized, with an expected difference between the means of 1.65 [25]; therefore, 11 cephalometric tracings per group were required for the study [32]. Eleven patients were enrolled: eight females (age 6.4 $\pm$ SD years) and three males (age: 12.4 $\pm$ SD years). Considering the tooth eruption stage for each patient, Hyrax RMEs were used on 10 patients. The RMEs were cemented onto the second primary molars on six patients, to the first permanent molars on three patients, and to the first permanent molars and premolars in one patient. One patient was treated with a Haas RME. A CBCT scan was performed before treatment (T0) and was repeated 6 months after the end of orthopedic therapy (T1). As CBCT is becoming more commonly used to quantitatively assess the effects of RME to overcome the limitations of 2D radiographs [33], it was necessary to repeat the CBCT 6 months after the end of the therapy to accurately assess the effects of the RME, especially on the transverse plane, such as the amount of disjunction of the alveolar bone and the dento-alveolar tipping of the first upper molars [34]. According to the protocol, two activations per day were required [35,36]. The duration of the active therapy was, on average, 3 weeks, and at the end of the activation time, the expanders were blocked with resin, metal or brass ligatures. It was necessary to wait at least 6 months after the removal of the expander to perform a new CBCT in order to prevent any image distortion during the scan. CBCTs at T0 and T1 were performed on each patient by the same operator using the same i-CAT machine (Imaging Science International, Hatfield, PA, USA), with a radiation dose of 2.5 mSv [37]. The following X-ray machine parameters were set: Tension: 120 kVP, Intensity: 3–7 mA, Focal spot: 0.5 mm, Voxel: 0.4 mm, Pixel: 0.4 mm, Grayscale: 14 bits, Scan time: 20 s, Detector material: amorphous silicon flat. Two programs were used in this study: Simplant OMS (version 2.1.3, Materialise NV, Leuven, Belgium) (Figure 1) and Delta-Dent (version 2.3, Outside Format, Pandino, Italy) (Figure 2). Both programs create radiological images in DICOM format that grant the capability to evaluate anatomical structures with more precision and without artifacts [38]. The operator can rely on visual and auditory support to optimize landmark positioning [1,3]. The section for the reconstruction of the DICOM images was set to start from 0.5 mm. The operator traced 25 landmarks, of which 19 were skeletal and 6 dental, enabling the programs to perform cephalometric measurements for the sagittal, vertical and transverse analysis [39,40]. The landmarks that were considered for analysis in the scans are presented in Table 1.

Regarding transverse plane analysis, two parameters were measured: firstly, the distance between the interproximal contact point on the mesial surface of the first right molar and the interproximal contact point on the mesial surface of the first left molar (6RIM-LIM) (Figure 3A), and secondly, the distance between the mesial surface of the first left molar and the mesial surface of the first right molar at the alveolar bone level (6RABM-6LABM) (Figure 3B).

In patients with mixed dentition, the second primary molar was set as the starting point. Concerning the vertical plane analysis, only linear parameters were considered: S-Go (posterior facial height), N-Me (anterior facial height), S-Go/N-Me, N-Ans (upper anterior facial height), Ans-Me (lower anterior facial height), N-Ans+Ans-Me (total anterior facial height), N-Ans/upper anterior facial height, Ans-Me/lower anterior facial height, LIf-LMf RIf-RMf. For the sagittal plane analysis, one linear and three angular parameters were evaluated: SNA, SNB, ANB, and A0B0 or Wits' index.

The data were submitted for statistical analysis. The mean and standard deviation were calculated as descriptive statistics for angular and linear measures. The normality of the distributions was assessed using the Kolmogorov–Smirnov test. Subsequently, an analysis of variance was accomplished with an ANOVA test followed by post hoc analysis with a Tukey test. The significance level was predetermined at $p < 0.05$.

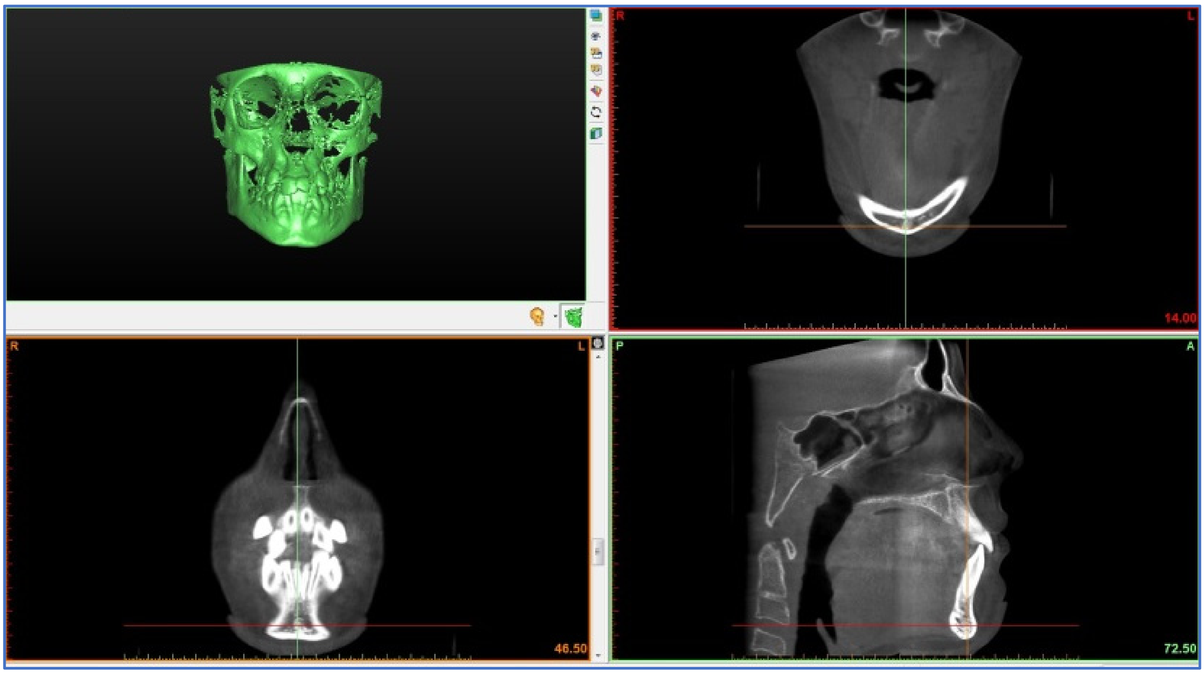


Figure 1. 3D rendering and vertical, transverse and sagittal projections provided by Simplant software.

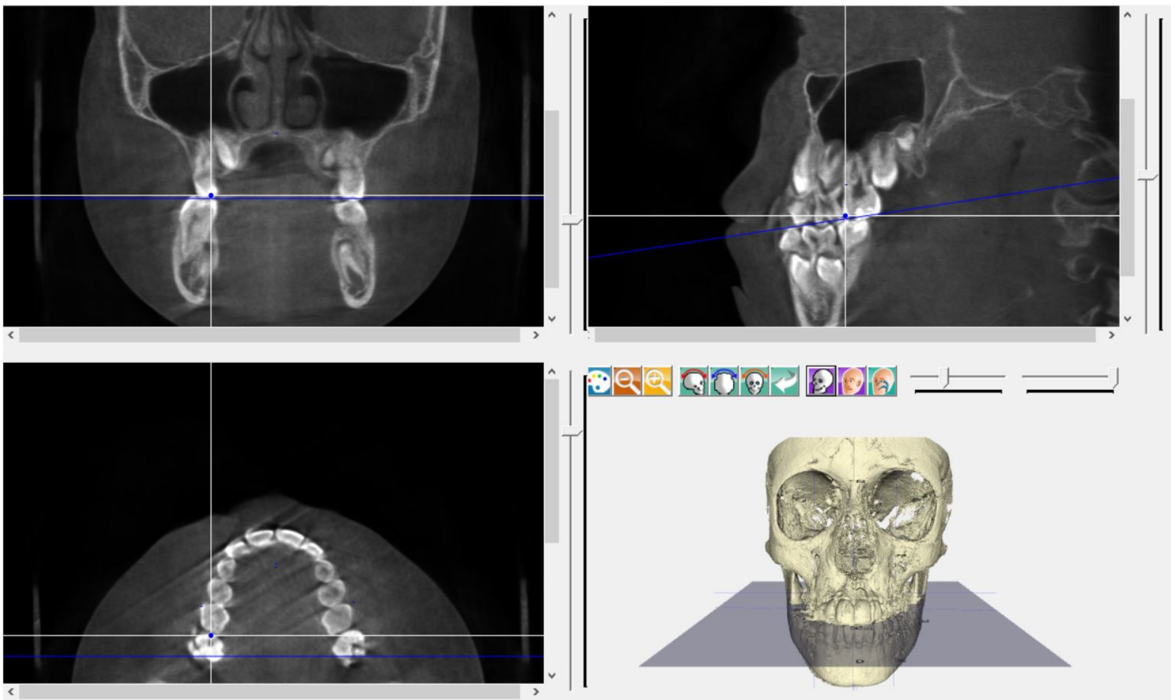
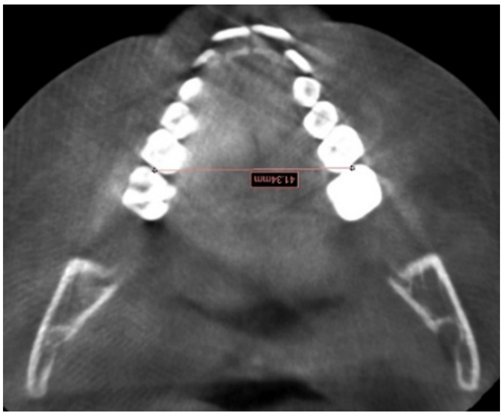


Figure 2. 3D rendering and vertical, transverse and sagittal projections provided by Delta-Dent software.

Table 1. Skeletal and dental landmarks for cephalometric analysis.

Skeletal Landmarks		
Point (Abbr.)	**Acronym**	**Explanation**
ANS	Anterior Nasal Spine	Anterior point on maxillary bone
PNS	Posterior Nasal Spine	Posterior limit of bony palate or maxilla
S	Sella Turcica	Midpoint of sella turcica
N	Nasion	Most anterior point on frontonasal suture
Point A	Subspinale	Most concave point on anterior maxilla
Point B	Supramentale	Most concave point on mandibular symphysis
Me	Menton	Lowest point on mandibular symphysis
Go	Gonion	Most posterior inferior point on angle of mandible It can also be constructed by bisecting the angle formed by intersection of mandibular plane and ramus of mandible
MGo	Mid-Gonion	Middle point between right gonion and left gonion
If	Infraorbital Foramen	RIf (right); LIf (left)
Mf	Mental Foramen	RMf (right); LMf (left)
S-Go	Sella–Gonion	Posterior facial height
N-Me	Nasion–Menton	Anterior facial height
N-Ans	Nasion–Anterior Nasal Spine	Upper anterior facial height
Ans-Me	Anterior Nasal Spine–Menton	Lower anterior facial height
N-Ans+Ans-Me	Nasion–Anterior Nasal Spine+Anterior Nasal Spine–Menton	Total anterior facial height
SNA	Angle between Sella/Nasion plane and Nasion/A plane	Antero-position of maxilla relative to upper cranial structures
SNB	Angle between Sella/Nasion plane and Nasion/B plane	Antero-position of mandible relative to upper cranial structures
ANB	SNA—SNB	Anteroposterior relationship of the mandible to the maxilla
Dental landmarks		
6RIM-6LIM		Distance between the interproximal contact point on the mesial surface of the first right molar and the interproximal contact point on the mesial surface of the first left molar
6RABM-6LABM		Distance between the mesial surface of the first right molar and the mesial surface of the first left molar at the alveolar bone level
A0B0		Orthogonal projections on the occlusal plane of points A and B
AOcl		Anterior occlusal point: middle point of the line that links upper and lower incisal points
MAOcl		Mid-anterior occlusal point: middle point between right AOcl and left AOcl
POcl		Posterior occlusal point: middle point of the occlusal surface of first permanent molars



(**A**) (**B**)

Figure 3. (**A**) 6RIM-6LIM measure; (**B**) 6RABM-6LABM.

3. Results

The data are shown in Table 2. Comparing the data before and after the maxillary expansion, both programs showed the following statistically significant differences ($p < 0.05$): 6RIM-6LIM and 6RABM-6LABM regarding the transversal analysis, N-Ans, S-Go and N-Ans+Ans-Me concerning the vertical analysis, while the skeletal class remained unaltered during the entire observation period. The posterior facial height values varied from T0 to T1.

Table 2. Mean values (standard deviation) of the 3D cephalometric analysis from the two programs.

Variables	Simplant		‡	Deltadent		‡	¥
	Pre-Exp	Post-Exp		Pre-Exp	Post-Exp		
6RABM-6LABM	36.18 (2.88) [a]	40.85 (2.59) [b]	$p < 0.0001$	36.47 (2.77) [a]	41.25 (2.74) [b]	$p < 0.0001$	NS
6RIM-6LIM	37.40 (2.79) [a]	41.71 (2.85) [b]	$p < 0.0001$	39.49 (6.58) [a]	43.97 (6.71) [b]	$p < 0.0001$	NS
RIf-RMf	54.63 (4.48) [a]	56.24 (4.93) [a]	NS	52.83 (5.29) [a]	56.54 (4.84) [b]	$p = 0.0211$	NS
LIf-LMf	54.10 (4.63) [a]	57.17 (4.96) [a]	NS	52.73 (5.39) [a]	56.28 (4.23) [b]	$p = 0.0039$	NS
N-Ans+Ans-Me	104.42 (11.09) [a]	107.00 (10.29) [b]	$p = 0.0436$	103.94 (10.05) [a]	107.50 (9.84) [b]	$p = 0.0078$	NS
N-Ans	46.39 (5.69) [a]	48.62 (5.62) [b]	$p = 0.0126$	46.28 (5.83) [a]	48.50 (5.94) [b]	$p = 0.0015$	NS
Ans-Me	58.03 (6.75) [a]	58.38 (6.14) [a]	NS	57.68 (5.84) [a]	59.00 (5.54) [a]	NS	NS
Sup/inf facial H	80.09 (9.85) [a]	83.27 (8.78) [a]	NS	80.36 (9.55) [a]	81.64 (10.48) [a]	NS	NS
S-Go	63.90 (6.16) [a]	66.62 (6.31) [b]	$p = 0.0024$	62.72 (5.42) [a]	65.05 (6.02) [b]	$p = 0.0279$	NS
N-Me	100.58 (10.35) [a]	103.47 (9.92) [a]	NS	101.07 (9.45) [a]	104.64 (9.50) [a]	NS	NS
S-Go/N-Me (%)	63.82 (4.98) [a]	64.64 (5.30) [a]	NS	62.28 (3.58) [a]	62.36 (3.72) [a]	NS	NS
SNA	83.12 (1.88) [a]	83.02 (1.83) [a]	NS	83.27 (1.64) [a]	82.75 (1.73) [a]	NS	NS
SNB	78.48 (2.93) [a]	78.44 (1.91) [a]	NS	78.53 (2.71) [a]	78.08 (1.71) [a]	NS	NS
ANB	4.71 (2.16) [a]	4.67 (1.79) [a]	NS	4.72 (2.22) [a]	4.73 (1.75) [a]	NS	NS
WITS	2.27 (0.85) [a]	2.83 (1.28) [a]	NS	3.21 (1.49) [a]	2.53 (1.35) [a]	NS	NS

Legend: means with the same superscript letters do not show statistically significant differences; ‡, intragroup differences; ¥, intergroup differences; NS, not significant.

Delta-Dent reported relevant discrepancies of pre- and post-expansion linear distances RIf-RMf and LIf-LMf, although these differences were not considered statistically significant by Simplant ($p > 0.05$). Delta-Dent provided higher values of standard deviation compared to Simplant, which can be considered more accurate because of its lower standard deviation.

None of the other parameters showed significant differences between the two programs ($p > 0.05$).

4. Discussion

As far as the RMEs' effects are concerned, in the literature, statistically significant changes were reported, not only on the transverse plane, but also on the vertical plane. The lowering of the bispinal plane increases the upper (N-Ans) and total anterior facial heights (N-Ans+Ans-Me) and creates a molar rotational hub, resulting in a mandibular post-rotation and in the growth of the anterior facial height [41]. The lowering of the palatal cusps determines the buccal tipping of the teeth with subsequent occlusal pre-contacts that lead to mandibular post-rotation, which temporarily increases the divergence [42]. Some authors reported significant differences on the sagittal plane: Baratieri et al. [41] showed a forward movement of the jaw, with an increase of SNB and a reduction of ANB that led to a spontaneous improvement of dental II classes in 75% of the sample. In the present pilot study, three patients with skeletal II class due to lower maxilla retraction showed a 2° decrease of ANB—six patients did not show any changes, and two patients showed a minimal increase. Recently, many studies in the literature observed significant improvements in skeletal II classes after RME therapy [41,43].

In the present pilot study, the only significant difference among the analyses performed by the two programs concerns the distance between the infraorbital and the mental foramina. According to both programs, the hemi-facial heights on the left and on the right side were increased from T0 and T1 in most of the patients; with Delta-Dent, this difference was found to be significant, whereas with Simplant, it was not. It is difficult to determine which values are more precise; however, it can be confirmed that some slight differences were reported between the two software programs. To the best of our knowledge, only one article in the literature compared two programs [20], and this study also concluded that is not possible to assess whether the discrepancies between the values measured are related to the limited size of the sample or to the different accuracy rate of each program. Furthermore, the sample is not homogeneous as far as the type of device and anchorage of the teeth are concerned. Ten patients were treated with the Hyrax RME, which is characterized by two acrylic pads connected by a stainless steel frame that distributes its forces on the palate, periodontal ligament and buccal bone; this device was cemented onto the second primary molars in six patients, to the first permanent molars in three patients, and to the first permanent molars and premolars in one patient. One patient was treated with a Haas RME, which is a stainless steel rigid structure that exerts its forces on the periodontium [8]. In the literature, some studies discuss how the type of expander may influence the outcomes of RME treatment. Weissheimer et al. evaluated the effects of RME treatment in patients treated with the same two expanders using CBCT, and observed that the Hyrax expander had major orthopedic effects and caused less tipping in the upper first molars [44]. However, Oliveira et al. three-dimensionally evaluated the outcomes of the Hyrax RME and Haas RME, and reported that the Haas expander induced more orthopedic movement, while the Hyrax expander promoted a major dentoalveolar expansion [45]. Other authors carried out similar comparative studies using 3D software and found no significant differences between the effects of the two expanders [46]. Some studies were carried out to determine whether there were any relevant differences as far as anchorage is concerned. Cerruto et al. compared the dental arch changes induced by RME treatment related to different types of anchorage and demonstrated how an RME anchored to the second primary molars is associated with an increased expansion in the anterior area and to a more relevant disto-rotation of the first maxillary molars compared to an RME anchored to the first permanent molars [47]. Another study published by Ugolini and his colleagues described how an expander anchored to the first permanent molars caused increased upper intermolar distance and the angulation of the upper maxillary molars compared to an expander anchored to the second primary molars, even though the latter resulted in an increased upper intercanine distance [48]. In addition, dental and skeletal outcomes may also be influenced by the activation protocol adopted. In the present pilot study, two activations per day were performed, but other protocols are described in the literature [49–51]. Baldini and his colleagues demonstrated how the activation protocol can affect the upper dental arch; according to their comparative study, a faster activation protocol could increase the midpalatal suture's anterior disjunction and promote major expansion in the molar area [52]. Furthermore, a faster activation protocol also resulted in an increased overjet, especially in subjects with lower skeletal maturation [53].

In the literature, other authors followed the same protocol as this study in which the timing of post-RME CBCT is not standardized. Most studies executed CBCT 6 months after RME treatment [31,54,55], but the timing varies between 3 and 12 months after treatment [33,56,57]. The present study has some limitations: RMEs' effects on the upper airways were not evaluated, and it would have been interesting to compare the results of the 3D analysis with those of a 2D analysis to evaluate the differences as far as the accuracy of the two methods is concerned. Furthermore, only two software programs were involved in the present study, and it is possible that different digital X ray machines could provide different results. In addition, further studies should evaluate the interface with optical impressions.

The digital cephalometric analysis of CBCT scans may become part of a completely digital workflow in the future; currently, orthodontics relies more and more frequently on computer-aided design and manufacturing (CAD-CAM) processes. Firstly, this process involves intra-oral scanners, which allow the acquisition of digital data. Subsequently, digital tridimensional design is performed and then the study models/appliances are produced using one of the currently available 3D printing techniques [58]. Digital workflow in orthodontics provides many advantages: it overcomes conventional impressions and gypsum casting and decreases laboratory working time [59].

The 3D cephalometric analysis provided by modern software may enable the avoidance of traditional cephalometry by offering all of the information required for an accurate diagnosis and appropriate treatment planning, both for orthodontics and orthognathic surgery [60].

Future studies will assess and compare the reliability of emerging software, as technology constantly develops, in order to perform an accurate tridimensional cephalometric analysis evaluating sagittal, transversal and vertical discrepancies and the outcomes of orthodontic treatment.

5. Conclusions

The most statistically significant differences between the two software programs related to the variables associated with the transverse plane, where the rapid maxillary expander is most effective. Both programs highlighted variations in the posterior and anterior facial heights on the vertical plane, while no differences were identified on the sagittal plane. The most challenging landmarks to locate were the infraorbital foramen and the mental foramen, which led to significant differences among the two programs. None of the other variables were shown to have statistically significant discrepancies between Simplant and Delta-Dent. According to the results obtained in this pilot study, both programs are reliable and efficient in the three-dimensional analysis of CBCT scans.

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Informed Consent Statement: Informed consent was obtained from all parents/guardians of the subjects involved in the study.

Data Availability Statement: Data are available upon reasonable request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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