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Three-dimensional dento-skeletal effects of mandibular midline distraction and surgically assisted rapid maxillary expansion: A retrospective study

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A B S T R A C T

It was the aim of the study to provide a three-dimensional evaluation of dento-skeletal effects following bone-borne vs tooth-borne mandibular midline distraction (MMD) and tooth-borne surgically assisted rapid maxillary expansion (SARME). A retrospective observational study was conducted. Cone beam computed tomography (CBCT) records were taken pre-operatively (T1), immediately post-distraction (T2) and 1 year post-operatively (T3). All included 30 patients had undergone MMD (20 bone-borne MMD; 10 tooth-borne MMD). A total of 20 bone-borne MMD and 8 tooth-borne MMD patients had simultaneously undergone tooth-borne SARME. At T1 vs T3, canine ($p = 0.007$; 26.0 ± 2.09 vs 29.2 ± 2.02) and first premolar ($p = 0.005$; 33.8 ± 2.70 vs 37.0 ± 2.43) showed significant expansion on the tip level for tooth-borne MMD. This was no significant on the apex level, indicating tipping. Bone-borne MMD showed a parallel distraction gap, whereas tooth-borne MMD showed a V-shape. There was a significant ($p = 0.017$; 138 ± 17.8 vs 141 ± 18.2) inter-condylar axes increase for bone-borne MMD. In conclusion, bone-borne vs tooth-borne MMD and tooth-borne SARME showed stable dento-skeletal effects at 1 year post-operatively. Bone-borne and tooth-borne MMD seemed not to be superior to each other. The choice of distractor type therefore depends more on anatomical and comfort factors.

1. Introduction

Transverse mandibular and maxillary discrepancies were historically managed with orthodontic dental expansion and/or dental extraction therapy. Orthodontic dental expansion to correct mandibular and maxillary arch dimensions could lead to unstable post-treatment results with relapse of the transverse skeletal discrepancies (Koudstaal et al., 2005; de Gijt et al., 2012). With these camouflage techniques, high relapse rates have been observed in the long-term (Conley and Legan, 2003). At 1 year of age, the mandibular symphysis closes, making surgery necessary to achieve bony expansion (Little, 1990; Sperber et al., 2001). Midpalatal suture expansion without surgery is predictable until approximately the age of 15 years (Wehrbein and Yildizhan, 2001). With the introduction of distraction for the facial skeleton in the early 1990s, new treatment options have become possible (McCarthy et al., 1992; Guerrero et al., 1997).

Mandibular midline distraction (MMD) is a proven surgical technique to widen the mandible and to solve transverse mandibular discrepancies with stable clinical outcomes in the long term (King et al., 2012; de Gijt et al., 2016). For transverse maxillary discrepancies, surgically assisted rapid maxillary expansion (SARME) is a well-known stable surgical technique (Koudstaal et al., 2009; de Gijt et al., 2017). Some specific cases require a combination of MMD and SARME, which is termed bimaxillary expansion (BiMEx) (Bianchi et al., 2017). Regarding distraction, there are various types of distractors such as tooth-borne, bone-borne or a combination of both (hybrid). For the mandible, after an osteotomy is performed in the midline, the type and attachment of the distractor creates different vectors in three-dimensional (3D) planes, since the temporomandibular joint (TMJ) is surrounded by soft tissue package and allows

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rotational, translational and horizontal movements. The biomechanical effects of the different types of distractors may influence the distraction and influence the TMJ (Mommaerts, 2001; Mommaerts et al., 2005; Gunbay et al., 2009). Until now, research on dento-skeletal effects of MMD using 3D imaging analysis techniques has been reported only scarcely (Landes et al., 2008; Seeberger et al., 2011a) and is, by and large, performed using conventional methods such as dental cast models and posterior-anterior cephalograms (Iseri and Malkoc, 2005; Malkoc et al., 2006; Alkan et al., 2007; King et al., 2012; de Gijt et al., 2016). On the other hand, SARME using 3D imaging analysis techniques is well reported (Seeberger et al., 2011b; Nada et al., 2012; Sygouros et al., 2014; Zandi et al., 2014; Oliveira et al., 2017; Ferraro-Bezerra et al., 2018; Huizinga et al., 2018; Kayalar et al., 2019). Little is known about the dento-skeletal effects of BiMEx using 3D imaging analysis techniques (Bianchi et al., 2017). As yet, there is no clinical study in the literature available comparing the dento-skeletal effects of bone-borne vs tooth-borne MMD using 3D imaging analysis techniques. Therefore, the main objective of this study was to provide a 3D evaluation of the dento-skeletal effects following bone-borne vs tooth-borne MMD and tooth-borne SARME.

2. Materials and methods

A retrospective observational study was conducted after approval was given by the Medical Ethics Committee of Erasmus MC, University Medical Center Rotterdam, the Netherlands (MEC-2013-367, protocol version 2021).

2.1. Patients

In this study, the following patients were included: patients who underwent bone-borne or tooth-borne MMD combined with tooth-borne SARME; and patients who underwent bone-borne or tooth-borne MMD solitary.

All included patients had undergone surgery between 2010 and 2016 at the Department of Oral and Maxillofacial Surgery, Erasmus MC, University Medical Center Rotterdam, the Netherlands. Inclusion criteria were transverse mandibular discrepancy (mandibular anterior and/or posterior crowding, uni- or bilateral crossbite) treated with MMD and transverse maxillary discrepancy (maxillary anterior and/or posterior crowding and/or uni- or bilateral crossbite) treated with SARME. Patients had to be at least 14 years of age.

Exclusion criteria were congenital (craniofacial) deformities, mental retardation, history of head injuries leaded to fractures in the area of interest, history of radiation therapy in the area of interest, additional orthognathic surgery following MMD (bilateral sagittal split osteotomy) or SARME (Le Fort I osteotomy) before 1 year post-treatment, and missing or insufficient cone beam computed tomography (CBCT) records.

The surgical technique for MMD was similar as described by Mommaerts (2001), combined with a bone-borne (Rotterdam Midline Distractor, KLS Martin Group, Germany) or tooth-borne distractor (Hyrax, the Netherlands) with anchorage on first premolar and molar.

Regarding SARME, the surgical technique was according to Koudstaal et al. (2009) combined with only a tooth-borne distractor (Hyrax, the Netherlands) with anchorage on first premolar and molar. Both surgical interventions were performed under general anesthesia. CBCT records were taken pre-operatively (T1), immediately post-distraction (T2), and 1 year post-operatively (T3).

2.2. CBCT analysis

CBCT scans (varying between 0.3 and 1 mm in slice thickness) were performed at T1, T2 and T3. The data were analyzed using the

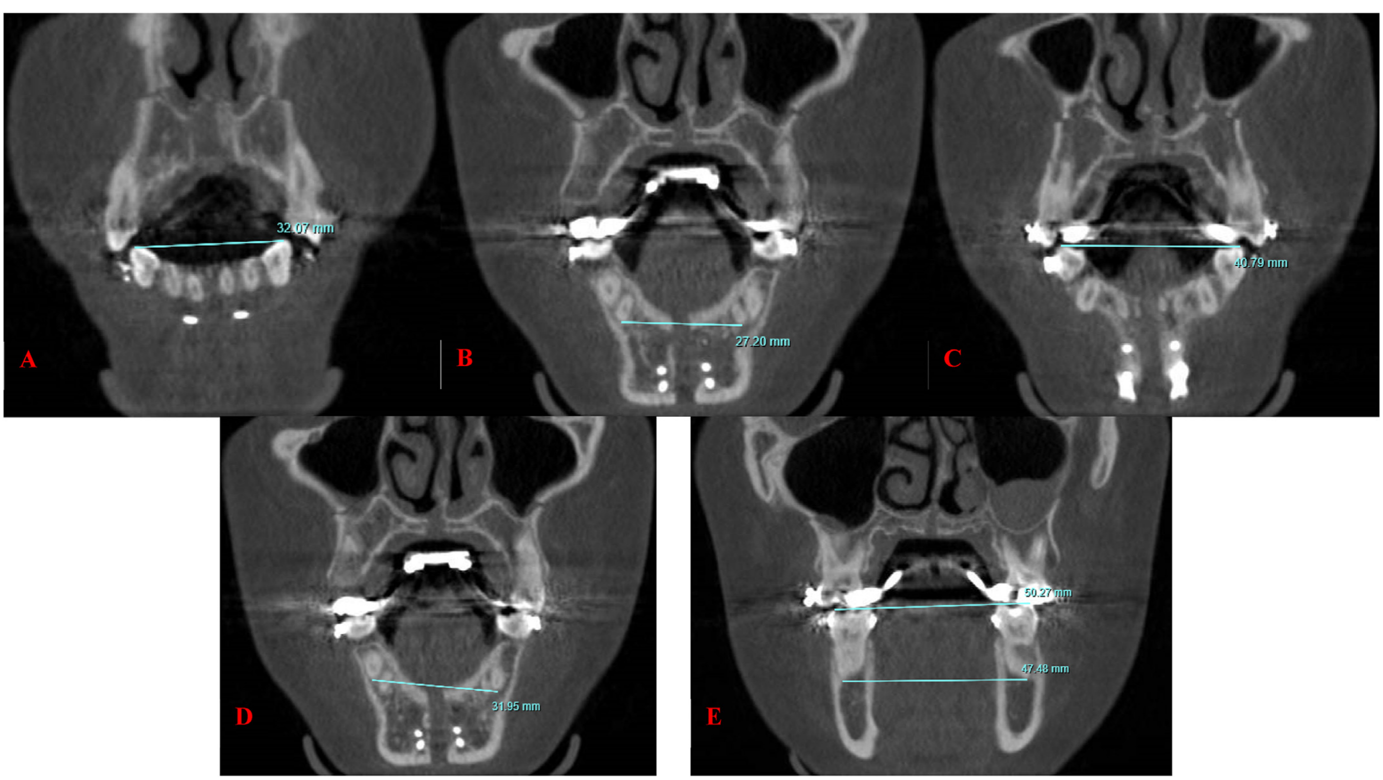


Fig. 1. Dental measurements regarding bone-borne vs tooth-borne MMD using coronal CBCT slices at T1, T2 and T3. A: MANICTD; B: MANICAD; C: MANIFPTD; D: MANIFPAD; E: MANIFMTD, MANIFMAD.

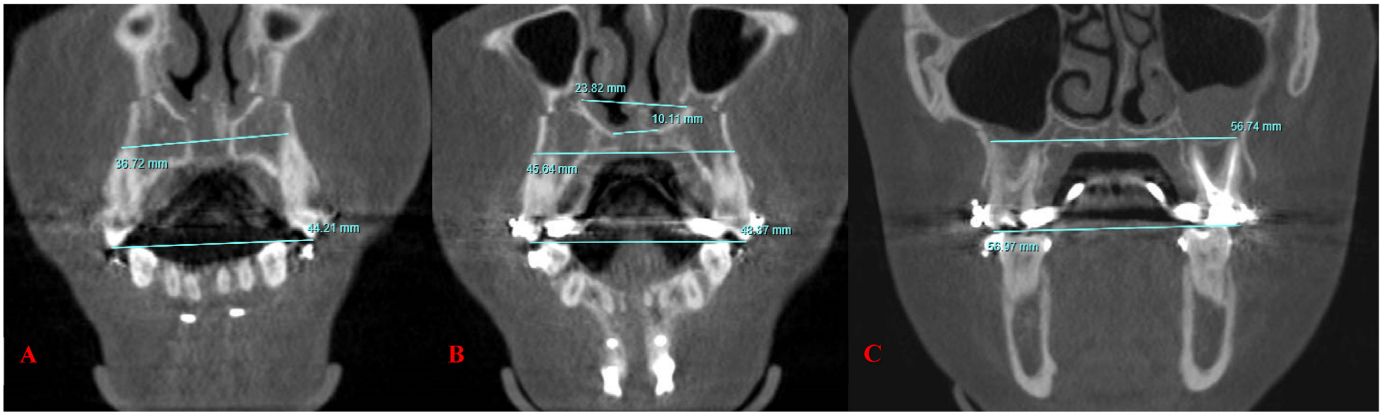


Fig. 2. Dental and skeletal measurements regarding tooth-borne SARME using coronal CBCT slices at T1, T2 and T3. A: MAXICTD, MAXICAD; B: MAXIFPTD, MAXIFPAD, MAXPALW, MAXPABW; C: MAXIFMTD, MAXIFMAD.

software Carestream Health, Inc. (2021) and Vue Motion (version 12.January 2, 4023).

Axial slices were reconstructed to coronal slices and 3D skeletal view if necessary.

At T1, T2 and T3 dental measurements were digitally performed as follows:

For bone-borne and tooth-borne MMD (Fig. 1), using coronal CBCT slices, the inter-canine tip distance (MANICTD); inter-canine apex distance (MANICAD); inter-first premolar buccal tip distance (MANIFPTD); inter-first premolar apex distance (MANIFPAD); inter-first molar disto-buccal tip distance (MANIFMTD); and inter-first molar distal apex distance (MANIFMAD).

For tooth-borne SARME (Fig. 2), using coronal CBCT slices, the inter-canine tip distance (MAXICTD); inter-canine apex distance (MAXICAD); inter-first premolar buccal tip distance (MAXIFPTD); inter-first premolar buccal apex distance (MAXIFPAD); inter-first molar disto-buccal tip distance (MAXIFMTD); and inter-first molar disto-buccal apex distance (MAXIFMAD).

At T1, T2 and T3 skeletal measurements were digitally performed as follows:

For bone-borne and tooth-borne MMD (Fig. 3), using axial CBCT slices and 3D skeletal view: inter-condylar distance (ICOND), from the most lateral condylar surface to its counterpart at the point of biggest condylar circumference; inter-condylar axes (ICONA), transecting median and lateral condylar pole at the point of biggest condylar circumference and measurement of the angle between the left and right side; ramal angle (RA), by creating a line from most lateral condylar surface to gonion and measurement of the angle between the left and right side; distraction gap angle (DGAPA), by creating a line at both sides of the osteotomy surface and measurement of the angle between the left and right side (only at T2).

For tooth-borne SARME (Fig. 2), using the same coronal CBCT slice as MAXIFPAD: piriform aperture lateral width (MAXPALW), from most lateral aspect of the piriform aperture to its counterpart; and piriform aperture base width (MAXPABW), from lowest aspect of the piriform aperture to its counterpart.

2.3. Statistical analysis

Descriptive statistics are used to characterize the study population. Distribution of the data was checked by plotting the histograms for the continuous variables. If this followed a normal distribution, a mean is presented, and for non-normal distributions medians are presented. To test the differences over time in mean distances, a Wilcoxon signed-rank test was used, because of the repeated measurements on a single sample. Furthermore, a Fisher exact test was used to analyze the difference in dental tipping between the bone-borne and tooth-borne MMD. For data handling and analyses, the Statistical Package of Social Sciences version 25.0 for Windows (IBM Corp, Armonk, NY, USA) was used. A p-value of less than 0.05 was considered to be statistically significant. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guideline was followed for reporting this study (von Elm et al., 2007).

Inter- and intra-observer agreement were assessed using an intraclass correlation coefficient (ICC). Therefore, 25% of all included bone-borne MMD and tooth-borne MMD patients were randomly selected and remeasured (by the first and third authors) to obtain inter- and intra-observer agreement. An ICC value between 0.75 and 0.90 was regarded as good, and above 0.90 as excellent (Koo and Li, 2016).

3. Results

3.1. Patients

In this study, 30 patients were included. All 30 patients had undergone MMD, of whom 20 patients had a bone-borne MMD and 10 patients had a tooth-borne MMD. All 20 bone-borne MMD patients and 8 of 10 tooth-borne MMD patients had undergone simultaneously tooth-borne SARME. At the time of surgery, the age of the patients ranged from 14 to 49 years. Table 1 lists the patient characteristics.

All patients completed the treatment and follow-up at T3, and the required expansion to resolve the transverse discrepancy was achieved.

3.2. CBCT dental analysis

3.2.1. Bone-borne vs tooth-borne MMD

The complete results of the CBCT analysis for the dental effects of bone-borne vs tooth-borne MMD are described in Table 2, Table 3 and Appendix I.

Regarding the bone-borne MMD, all inter-dental distances were significantly increased at T1 vs T2 and T1 vs T3. At T2 vs T3 MANICTD and MANIFPAD decreased significantly; however, these distances remained significant at T1 vs T3. MANICAD, MANIFPTD, MANIFMTD and MANIFMAD remained stable and were not significant at T2 vs T3. Concerning the mean distance difference on tip and apex level at T2-T1 and T3-T1, only MANICTD (2.89 ± 2.39) vs.

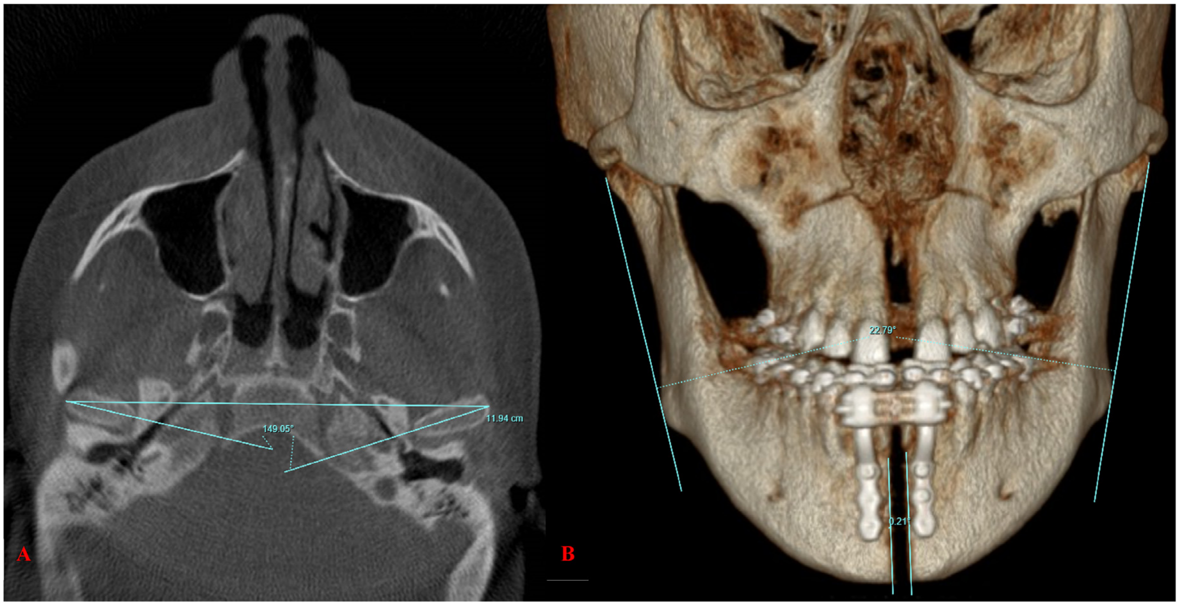


Fig. 3. Skeletal measurements regarding bone-borne vs tooth-borne MMD using axial CBCT slices and 3D skeletal view at T1, T2 and T3. A: ICOND, ICONA; B: RA, DGAPA (only at T2).

Table 1
Baseline patient characteristics.

T1-T3	BB MMD:TB SARME	TB MMD:TB SARME
Number of patients	20:20	10:8
Mean age (range), years	29.8 (16–45)	29.5 (14–49)
Female to male ratio	11F:9 M	6F:4 M

BB MMD, bone-borne mandibular midline distraction; F, female; M, male; TB MMD, tooth-borne mandibular midline distraction; TB SARME, tooth-borne surgically assisted rapid maxillary expansion.

MANICAD (5.21 ± 2.51)at T3-T1 differed significantly (p = 0.008), which indicates tipping.

Regarding tooth-borne MMD, all inter-dental distances were significantly increased at T1 vs T2. At T2 vs T3, only MANIFMTD decreased significantly (p = 0.015), whereas all other inter-dental distances did not change significantly. At T1 vs T3, MANICAD and MANIFPAD did not change significantly, whereas MANICTD (p = 0.007) and MANIFPTD (p = 0.005) were increased significantly which indicate tipping. Only MANIFMTD and MANIFMAD were both increased significantly on the tip and apex level at T1 vs T3. Concerning the mean distance differences on tip and apex level at T2-T1, MANICTD (3.85 ± 1.06) vs MANICAD (1.39 ± 1.25) differed significantly (p = 0.005). However, at T3-T1, this difference was no longer significant. Furthermore, MANIFPTD (3.71 ± 1.12) vs MANIFPAD (1.15 ± 0.92) differed significantly (p = 0.005) at T2-T1. At T3-T1, these differences remained significant (p = 0.007) for MANIFPTD (3.25 ± 1.58) vs MANIFPAD (0.12 ± 1.61). This finding confirms tipping. At T2-T1 and T3-T1, MANIFMTD vs MANIFMAD did not differ significantly.

Table 2
Bone-borne vs tooth-borne MMD, mean distance on tip and apex level.

	MANICTD *T1* mean + - SD	MANICTD *T2* mean + - SD	MANICTD *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	26,9 +- 3,42	32,4 +- 2,28	29,7 +- 2,12	**p < 0,001**	**p = 0,001**	**p < 0,001**
MMD TB (n = 10)	26,0 +- 2,09	29,9 +- 1,40	29,2 +- 2,02	**p = 0,002**	p = 0,203	**p = 0,007**
	MANICAD *T1* mean + - SD	**MANICAD** *T2* mean + - SD	**MANICAD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	21,0 +- 2,50	26,1 +- 3,30	26,2 +- 3,11	**p < 0,001**	p = 0,455	**p < 0,001**
MMD TB (n = 10)	21,1 +- 4,84	22,5 +- 4,61	21,9 +- 4,22	**p = 0,017**	p = 0,092	p = 0,333
	MANIFPTD *T1* mean + - SD	**MANIFPTD** *T2* mean + - SD	**MANIFPTD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	34,4 +- 3,24	39,5 +- 2,78	38,8 +- 2,35	**p < 0,001**	p = 0,104	**p < 0,001**
MMD TB (n = 10)	33,8 +- 2,70	37,5 +- 2,46	37,0 +- 2,43	**p = 0,005**	p = 0,415	**p = 0,005**
	MANIFPAD *T1* mean + - SD	**MANIFPAD** *T2* mean + - SD	**MANIFPAD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	31,3 +- 3,31	35,7 +- 3,14	34,9 +- 3,26	**p < 0,001**	**p = 0,042**	**p < 0,001**
MMD TB (n = 10)	31,0 +- 2,10	32,1 +- 2,19	31,1 +- 2,06	**p = 0,005**	p = 0,074	p = 0,80
	MANIFMTD *T1* mean + - SD	**MANIFMTD** *T2* mean + - SD	**MANIFMTD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 19)	46,1 +- 5,19	50,0 +- 4,87	50,0 +- 2,97	**p < 0,001**	p = 0,601	**p < 0,001**
MMD TB (n = 9)	47,0 +- 4,45	51,3 +- 3,68	50,1 +- 3,69	**p = 0,008**	**p = 0,015**	**p = 0,011**
	MANIFMAD *T1* mean + - SD	**MANIFMAD** *T2* mean + - SD	**MANIFMAD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 19)	50,5 +- 3,14	53,6 +- 3,82	53,0 +- 3,78	**p = 0,001**	p = 0,084	**p = 0,003**
MMD TB (n = 9)	49,8 +- 3,01	53,4 +- 3,97	51,7 +- 3,63	**p = 0,011**	p = 0,314	**p = 0,066**

*p-value based on the Wilcoxon signed rank test.

Table 3
Bone-borne vs tooth-borne MMD, mean distance difference on tip and apex level.

	MANICTD *T2-T1* mean + - SD	MANICAD *T2-T1* mean + - SD	MANICTD *T3-T1* mean + - SD	MANICAD *T3-T1* mean + - SD	MANICTD *T2-T1* vs MANICAD *T2-T1*	MANICTD *T3-T1* vs MANICAD *T3-T1*
MMD BB (n = 20)	5,52 +- 2,23	5,07 +- 2,40	2,89 +- 2,39	5,21 +- 2,51	p = 0,204	**p = 0,008**
MMD TB (n = 10)	3,85 +- 1,06	1,39 +- 1,25	3,12 +- 1,60	0,74 +- 2,82	**p = 0,005**	p = 0,139
	MANIFPTD *T2-T1* mean + - SD	**MANIFPAD** *T2-T1* mean + - SD	**MANIFPTD** *T3-T1* mean + - SD	**MANIFPAD** *T3-T1* mean + - SD	**MANIFPTD** *T2-T1* vs **MANIFPAD** *T2-T1*	**MANIFPTD** *T3-T1* vs **MANIFPAD** *T3-T1*
MMD BB (n = 20)	5,12 +- 2,24	4,43 +- 2,66	4,38 +- 2,29	3,61 +- 2,90	p = 0,145	p = 0,247
MMD TB (n = 10)	3,71 +- 1,12	1,15 +- 0,92	3,25 +- 1,58	0,12 +- 1,61	**p = 0,005**	**p = 0,007**
	MANIFMTD *T2-T1* mean + - SD	**MANIFMAD** *T2-T1* mean + - SD	**MANIFMTD** *T3-T1* mean + - SD	**MANIFMAD** *T3-T1* mean + - SD	**MANIFMTD** *T2-T1* vs **MANIFMAD** *T2-T1*	**MANIFMTD** *T3-T1* vs **MANIFMAD** *T3-T1*
MMD BB (n = 19)	3,89 +- 2,27	3,14 +- 2,87	3,94 +- 2,89	2,56 +- 2,85	p = 0,227	p = 0,227
MMD TB (n = 9)	4,25 +- 1,70	2,64 +- 1,57	3,10 +- 2,02	1,97 +- 2,38	p = 0,110	p = 0,314

*p-value based on the Wilcoxon signed rank test.

3.2.2. Tooth-borne SARME

The complete results of the CBCT analysis for the dental effects of tooth-borne SARME are described in Table 4, Table 5 and Appendix II.

At T1 vs T2, all inter-dental distances were increased significantly. At T2 vs T3, only MAXICTD decreased significantly ($p = 0.036$) when combined with tooth-borne MMD. At T1 vs T3, all inter-dental distances remained significantly increased, except MAXICAD when combined with tooth-borne MMD. Concerning the mean distance differences on tip and apex level at T2-T1, MAXICTD vs MAXICAD differed significantly when combined with bone-borne MMD ($p < 0.001$) and tooth-borne MMD ($p = 0.012$). This finding confirms tipping. However, at T3-T1, these differences were no longer significant, indicating a more parallel-wise expansion of the canines on the tip and apex level. Regarding MAXIFPTD vs MAXIFPAD at T2-T1 and T3-T1, these differences were significant except when combined with bone-borne MMD at T2-T1 ($p = 0.091$). At T2-T1, MAXIFMTD vs MAXIFMAD differed significantly when combined with bone-borne MMD ($p = 0.002$) and tooth-borne MMD ($p = 0.012$). However, at T3-T1, these differences were no longer significant, suggesting a more parallel-wise expansion of the first molars on tip and apex level.

3.3. CBCT skeletal analysis

3.3.1. Bone-borne vs tooth-borne MMD

The complete results of the CBCT analysis for the skeletal effects of bone-borne vs tooth-borne MMD are described in Table 6 and Appendix III.

At T1 vs T2, T2 vs T3 and T1 vs T3 RA did not change significantly for bone-borne and tooth-borne MMD. Only at T1 vs T3 ICONA was increased significantly ($p = 0.017$) for bone-borne MMD. ICOND did not change significantly for bone-borne and tooth-borne MMD at T1 vs T2, T2 vs T3 and T1 vs T3. DGAPA for bone-borne MMD (1.54 ± 1.93) vs tooth-borne MMD (3.02 ± 2.31) differed significantly ($p = 0.040$), indicating a V-shape distraction gap for tooth-borne

Table 4
Tooth-borne SARME, mean distance on tip and apex level.

	MAXICTD *T1* mean + - SD	MAXICTD *T2* mean + - SD	MAXICTD *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	34,6 +- 3,38	41,1 +- 3,13	39,6 +- 3,24	**p < 0,001**	p = 0,057	**p < 0,001**
MMD TB (n = 8)	34,6 +- 2,89	39,5 +- 3,31	38,2 +- 2,97	**p = 0,012**	**p = 0,036**	**p = 0,012**
	MAXICAD *T1* mean + - SD	**MAXICAD** *T2* mean + - SD	**MAXICAD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	29,5 +- 4,46	34,1 +- 4,07	34,1 +- 3,78	**p < 0,001**	p = 0,867	**p < 0,001**
MMD TB (n = 8)	30,8 +- 3,02	33,7 +- 2,78	32,4 +- 3,42	**p = 0,01**	p = 0,123	p = 0,123
	MAXIFPTD *T1* mean + - SD	**MAXIFPTD** *T2* mean + - SD	**MAXIFPTD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 19)	40,8 +- 4,32	47,1 +- 2,63	46,9 +- 2,32	**p < 0,001**	p = 0,63	**p < 0,001**
MMD TB (n = 8)	39,8 +- 4,14	46,0 +- 3,76	45,3 +- 3,46	**p = 0,012**	p = 0,068	**p = 0,012**
	MAXIFPAD *T1* mean + - SD	**MAXIFPAD** *T2* mean + - SD	**MAXIFPAD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 19)	39,1 +- 4,59	44,1 +- 3,86	43,6 +- 4,29	**p < 0,001**	p = 0,33	**p < 0,001**
MMD TB (n = 8)	40,6 +- 4,66	43,3 +- 4,42	43,3 +- 4,43	**p = 0,012**	p = 0,33	**p = 0,025**
	MAXIFMTD *T1* mean + - SD	**MAXIFMTD** *T2* mean + - SD	**MAXIFMTD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	52,7 +- 4,88	57,4 +- 3,42	57,0 +- 4,04	**p < 0,001**	p = 0,30	**p < 0,001**
MMD TB (n = 8)	52,6 +- 5,01	56,8 +- 5,09	56,0 +- 4,24	**p = 0,012**	p = 0,093	**p = 0,012**
	MAXIFMAD *T1* mean + - SD	**MAXIFMAD** *T2* mean + - SD	**MAXIFMAD** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 20)	54,4 +- 6,14	57,3 +- 5,58	57,4 +- 5,78	**p < 0,001**	p = 0,72	**p < 0,001**
MMD TB (n = 8)	56,2 +- 6,67	58,6 +- 6,12	58,7 +- 6,56	**p = 0,012**	p = 0,89	**p = 0,012**

*p-value based on the Wilcoxon signed rank test.

Table 5
Tooth-borne SARME, mean distance difference on tip and apex level.

	MAXICTD *T2-T1* mean + - SD	MAXICAD *T2-T1* mean + - SD	MAXICTD *T3-T1* mean + - SD	MAXICAD *T3-T1* mean + - SD	MAXICTD *T2-T1* vs MAXICAD *T2-T1*	MAXICTD *T3-T1* vs MAXICAD *T3-T1*
MMD BB (n = 20)	6,55 +- 2,92	4,67 +- 2,18	5,04 +- 2,65	4,63 +- 2,74	**p < 0,001**	p = 0,37
MMD TB (n = 8)	4,97 +- 1,26	2,89 +- 1,35	3,62 +- 1,51	1,61 +- 2,48	**p = 0,012**	p = 0,21
	MAXIFPTD *T2-T1* mean + - SD	**MAXIFPAD** *T2-T1* mean + - SD	**MAXIFPTD** *T3-T1* mean + - SD	**MAXIFPAD** *T3-T1* mean + - SD	**MAXIFPTD** *T2-T1* vs **MAXIFPAD** *T2-T1*	**MAXIFPTD** *T3-T1* vs **MAXIFPAD** *T3-T1*
MMD BB (n = 19)	6,31 +- 3,44	5,02 +- 2,52	6,13 +- 4,09	4,51 +- 2,44	p = 0,091	**p = 0,044**
MMD TB (n = 8)	6,24 +- 1,60	3,31 +- 1,44	5,47 +- 1,53	2,75 +- 1,85	**p = 0,012**	**p = 0,017**
	MAXIFMTD *T2-T1* mean + - SD	**MAXIFMAD** *T2-T1* mean + - SD	**MAXIFMTD** *T3-T1* mean + - SD	**MAXIFMAD** *T3-T1* mean + - SD	**MAXIFMTD** *T2-T1* vs **MAXIFMAD** *T2-T1*	**MAXIFMTD** *T3-T1* vs **MAXIFMAD** *T3-T1*
MMD BB (n = 20)	4,79 +- 2,54	2,87 +- 1,29	4,33 +- 2,28	3,03 +-2,01	**p = 0,002**	p = 0,059
MMD TB (n = 8)	4,20 +- 1,70	2,41 +- 1,47	3,46 +- 1,53	2,45 +- 1,67	**p = 0,012**	p = 0,080

*p-value based on the Wilcoxon signed rank test.

MMD and thus anterior mandibular skeletal tipping in the coronal plane. Fig. 4 provides an example of the difference of DGAPA for bone-borne vs tooth-borne MMD in the 3D skeletal view at T2.

3.3.2. *Tooth-borne SARME*

The complete results of the CBCT analysis for the skeletal effects of tooth-borne SARME are described in Table 7 and Appendix IV.

At T1 vs T2, MAXPALW increased significantly when combined with bone-borne MMD ($p < 0.001$) and tooth-borne MMD ($p = 0.012$). However, at T2 vs T3 this was decreased significantly when combined with bone-borne MMD ($p = 0.001$) and tooth-borne MMD ($p = 0.012$). At T1 vs T3, MAXPALW did not change significantly at the end.

MAXPABW increased significantly when combined with bone-borne MMD ($p < 0.001$) and tooth-borne MMD ($p = 0.012$) at T1 vs T2. However, at T2 vs T3, this was decreased significantly when combined with bone-borne MMD ($p = 0.004$) and tooth-borne MMD ($p = 0.012$). At T1 vs T3, MAXPABW remained significantly increased only when combined with bone-borne MMD ($p < 0.001$).

3.4. *Reliability analysis*

The ICC for each separate measurement is provided in Table 8. Both inter- and intra-observer reliability ranged between 0.757 [0.421–0.911] and 0.999 [0.997–1.00], indicating good to excellent agreement.

4. Discussion

This retrospective observational study was performed to provide a 3D evaluation of the dento-skeletal effects following bone-borne vs tooth-borne MMD and tooth-borne SARME or bone-borne vs tooth-borne MMD solitary. CBCT scans were performed pre-operatively (T1), immediately post-distraction (T2), and 1 year post-operatively (T3) and were analyzed as described in the Materials and Methods section.

4.1. *Bone-borne vs tooth-borne MMD*

The results showed that all inter-dental distances were significantly increased at T1 vs T2 and T1 vs T3 with the bone-borne MMD. These outcomes are in line with findings by de Gijt et al. (2016).

At T2 vs T3, mandibular inter-canine tip distance and mandibular inter-first premolar apex distance decreased significantly; however, these distances remained significant at T1 vs T3. These decreases and the significant tipping ($p = 0.008$) of mandibular inter-canine tip distance vs mandibular inter-canine apex distance at T3-T1 may be the result of the orthodontic treatment moving the

Table 6
Bone-borne vs tooth-borne MMD, skeletal effects.

	RA *T1* mean + - SD	RA *T2* mean + - SD	RA *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 17)	24,7 +- 5,10	24,7 +- 6,30	24,2 +- 5,57	p = 0,62	p = 0,41	p = 0,25
MMD TB (n = 10)	24,5 +- 5,80	26,0 +- 5,28	25,4 +- 5,38	p = 0,074	p = 0,33	p = 0,22
	ICONA *T1* mean + - SD	**ICONA** *T2* mean + - SD	**ICONA** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 17)	138 +- 17,8	140 +- 17,8	141 +- 18,2	p = 0,193	p = 0,523	**p = 0,017**
MMD TB (n = 10)	126 +- 8,99	127 +- 8,79	127 +- 9,19	p = 0,445	p = 0,799	p = 0,285
	ICOND *T1* mean + - SD	**ICOND** *T2* mean + - SD	**ICOND** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 17)	11,5 +- 0,67	11,4 +- 0,78	11,4 +- 0,78	p = 0,118	p = 0,962	p = 0,256
MMD TB (n = 10)	11,3 +- 0,30	11,4 +- 0,51	11,2 +- 0,39	p = 0,286	p = 0,059	p = 0,241
		DGAPA *T2* mean + - SD				DGAPA *T2* BB vs TB
MMD BB (n = 20)		1,54 +- 1,93				**p = 0,040**
MMD TB (n = 10)		3,02 +- 2,31				

*p-value based on the Wilcoxon signed rank test.
*p-value based on Fisher's exact test.

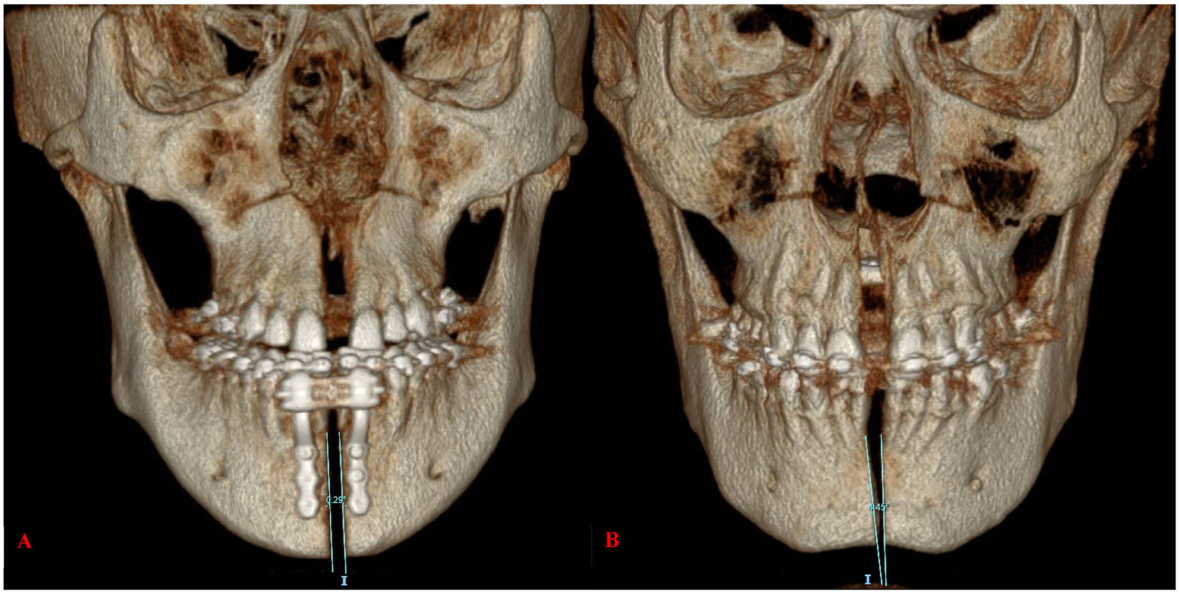


Fig. 4. Difference of DGAPA in the 3D skeletal view at T2. A: Bone-borne MMD; B: Tooth-borne MMD.

Table 7
Tooth-borne SARME, skeletal effects.

	MAXPALW *T1* mean + - SD	MAXPALW *T2* mean + - SD	MAXPALW *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 18) T1 = 20, T2 = 18, T3 = 20	25,7 +- 3,02	27,7 +- 3,56	26,3 +- 3,34	**p < 0,001**	**p = 0,001**	p = 0,204
MMD TB (n = 8)	26,9 +- 3,02	28,3 +- 2,59	27,6 +- 2,48	**p = 0,012**	**p = 0,012**	p = 0,093
	MAXPABW *T1* mean + - SD	**MAXPABW** *T2* mean + - SD	**MAXPABW** *T3* mean + - SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
MMD BB (n = 18) T1 = 20, T2 = 18, T3 = 20	11,6 +- 3,47	15,1 +- 3,04	14,1 +- 2,69	**p < 0,001**	**p = 0,004**	**p < 0,001**
MMD TB (n = 10)	10,4 +- 3,85	13,3 +- 3,25	11,8 +- 2,89	**p = 0,012**	**p = 0,012**	p = 0,107

*p-value based on the Wilcoxon signed rank test.

Table 8
ICC for each separate measurement.

ICC	Intra-observer	Inter-observer
MANICTD MAXICTD	0,994 [0,99–1,00]	0,989 [0,99–1,00]
MANICAD MAXICAD	0,99 [0,985–1,00]	0,995 [0,989–0,997]
MANIFPTD MAXIFPTD	0,990 [0,964–0,996]	0,992 [0,964–0,996]
MANIFPAD MAXIFPAD	0,990 [0,976–0,996]	0,982 [0,962–0,991]
MANIFMTD MAXIFMTD	0,995 [0,990–0,998]	0,994 [0,988–0,997]
MANIFMAD MAXIFMAD	0,992 [0.983–0,996]	0,991 [0,982–0,996]
ICOND	0,999 [0,996–1,00]	0,998 [0,995–0,999]
RA	0,994 [0,981–0,998]	0,978 [0,930–0,993]
ICONA	0,999 [0,997–1,00]	0,998 [0,993–0,999]
DGAPA	0,998 [0,988–1,00]	0,998 [0,978–1,00]
MAXPALW	0,81 [0,519–0,932]	0,757 [0,421–0,911]
MAXPABW	0,92 [0,782–0,974]	0,901 [0,738–0,965]

ICC based on a Two-way random model for absolute agreement for single measures.

canines and first premolars into the distraction gap in order to close the central diastema. Due to the curved body shape of the mandible, this effect is smaller for the (pre)molar region.

Regarding tooth-borne MMD, all inter-dental distances were significantly increased at T1 vs T2.

At T1 vs T3, mandibular inter-canine apex distance and mandibular inter-first premolar apex distance did not change significantly, whereas mandibular inter-canine tip distance ($p = 0.007$) and mandibular inter-first premolar tip distance ($p = 0.005$) were increased significantly, which indicates tipping. These results are broadly in line with those of Seeberger et al., indicating significant tipping of the (first) premolar due to the anchorage and distraction forces of the tooth-borne distractor (Seeberger et al., 2011a). However, next to tipping of the (first) premolar, they found significant tipping of the (first) molar. Here, it should be noted that their results were obtained 3 months after surgery and before orthodontic treatment, which makes comparison difficult. In the current study, no significant tipping of the (first) molar was observed for the tooth-borne distractor at T2-T1 and T3-T1. This could also be related to the anatomical difference s between the (first) molar with two roots vs the (first) premolar with one conically shaped root, which is less resistance for distraction forces as anchorage on the dento-alveolar level. In contrast, the applied forces with the bone-borne distractor are at the basal bone level, resulting in no significant tipping ($p = 0.247$) of the (first) premolar at T3-T1, which indicates a more parallel expansion of the (first) premolars on tip and apex level. This outcome is in line with the skeletal effects of the bone-borne MMD regarding distraction gap angle. At T2, the distraction gap angle for bone-borne MMD vs tooth-borne MMD differed significantly ($p = 0.040$), indicating a more parallel distraction gap at the basal bone level and without anterior mandibular skeletal tipping in the coronal plane for bone-borne MMD. This outcome also indicate a V-shaped distraction gap for tooth-borne MMD and thus anterior mandibular skeletal tipping in the coronal plane suggesting dento-skeletal tipping of the mandibular canine and first premolar. At T1 vs T3, no significant change was observed in inter-condylar distance for bone-borne MMD and tooth-borne MMD. These outcomes are in line with those of Seeberger et al. (2011a), as they observed significant ($p = 0.001$) tipping of the mandibular corpus and no significant changes in inter-condylar distance for tooth-borne MMD.

Theoretically, tooth-borne MMD applies distraction forces more posterolaterally due to the anchorage on the (pre)molars. However in this study, at T1 vs T2, T2 vs T3 and T1 vs T3, no significant changes were observed in ramal angle and inter-condylar distance for tooth-borne MMD and bone-borne MMD, applying distraction forces more anteriorly at the basal bone level. This is in concordance with the outcomes of Bianchi et al. for bone-borne MMD, as they observed no significant changes in inter-condylar distance and ramal angle (Bianchi et al., 2017). Landes et al. observed a significant ($p = 0.02$) decrease in inter-condylar distance for bone-borne MMD (Landes et al., 2008); however, this outcome should be interpreted very carefully given the low number ($n = 9$) of patients included. In the same study, condylar angulation and vertical medial, cranial and lateral distances to the fossa remain unchanged (Landes et al., 2008). This outcome is in contrast to the current study, as there was a significant ($p = 0.017$) increase in inter-condylar axes for bone-borne MMD at T1 vs T3, which indicates a condylar exorotation in the axial plane. Although it was not significant, it is remarkable that the inter-condylar axes were slightly increased at T1 vs T2 and T2 vs T3, indicating that the soft tissue package surrounding the TMJ adapts over time to the anterior parallel wise distraction for bone-borne MMD.

4.2. Tooth-borne SARME

Concerning tooth-borne SARME, at T1 vs T2, all inter-dental distances were increased significantly. At T1 vs T3, all inter-dental distances remained significantly increased when combined with bone-borne MMD. These outcomes are in accordance with de Gijt et al. (2017).

Moreover, at T3-T1, significant tipping was observed for the (first) premolar when combined with bone-borne MMD ($p = 0.044$) and tooth-borne MMD ($p = 0.017$). This outcome is in line with Seeberger et al. (2011b), as they observed significant ($p < 0.01$) tipping of the anchorage (pre)molars for tooth-borne SARME. In contrast to their study, in this study significant tipping of the molars at T2-T1 did not remain significant at T3-T1, indicating a more parallel-wise correction when combined with bone-borne and tooth-borne MMD. However, it should be noted that their results were obtained 3 months after surgery and before orthodontic treatment, which makes comparison difficult. Theoretically, for SARME, tooth-borne distractors perform their distraction forces on dento-alveolar level and bone-borne distractors at higher position in the palatal vault. However, after performing osteotomies, the maxilla is still connected to the skull base, and during expansion there is more resistance at midpalatal suture level. Moreover, no pterygomaxillary disjunction was performed in included cases. Therefore, during expansion the resistance is located at cranial level (midpalatal suture) and posterior (pterygomaxillary junction) for tooth- and bone-borne distractors both. In the current study, a significant increase was observed in the piriform aperture base width and piriform aperture lateral width at T1 vs T2. However, at T1 vs T3, only the piriform aperture base width remained significantly increased when combined with bone-borne MMD ($p < 0.001$). This outcome indicates a (reverse) V-shaped widening of the nasal floor in the coronal plane (skeletal tipping) and is in concordance with the outcomes of Seeberger et al. and Zandi et al. for tooth-borne SARME (Seeberger et al., 2011b; Zandi et al., 2014). In addition, Zandi et al. did not find any significant difference in skeletal tipping for bone-borne vs tooth-borne SARME (Zandi et al., 2014).

Moreover, it should be noted that the current findings regarding skeletal effects in the nasal region broadly correlate with previous findings regarding 3D soft tissue effects of bone-borne MMD and tooth-borne SARME (Gül et al., 2019). A significant mean increase of 2.20 mm in the inter-alar width (corresponding with the piriform aperture lateral width) and a non-significant mean increase of 1.77 mm in the inter-alar curvature point width (corresponding with the piriform aperture base width) were presented. It can be concluded that the skeletal effects do not project in the same proportion to the soft tissue effects regarding tooth-borne SARME. These findings suggest that besides the observed hard tissue effects, other factors could influence these soft tissue effects, such as the circumvestibular approach, anterior nasal spine exposure and not applying an alar base cinch suture during surgery.

A limitation of this study is the sample size ($n = 20$ with bone-borne MMD and $n = 10$ with a tooth-borne MMD), which might have led to bias. At 1 year post-operatively, this study showed stable dento-skeletal effects of bone-borne vs tooth-borne MMD and tooth-borne SARME. However, the follow-up period is limited to 1 year, since the majority of the included patients underwent additional surgery directly after 1 year. Therefore, long-term 3D evaluation of the dento-skeletal effects following bone-borne vs tooth-borne MMD and tooth-borne SARME or bone-borne vs tooth-borne MMD solitary was not possible. Another limitation of the current study may be the use of multiple tests. However, the majority of the p-values reached a high level of significance, which makes correction of the p-value relatively unnecessary.

Based on the current results, it can be concluded that bone-borne and tooth-borne MMD both are stable techniques to achieve transversal (dento-skeletal) expansion. Tipping of the canine and (first) premolar combined with a V-shaped anterior mandibular skeletal tipping in the coronal plane is remarkable for tooth-borne MMD. However, a long-term follow-up of tooth-borne MMD vs a combination of tooth-borne and bone-borne (hybrid) MMD showed that both are a viable treatment options (Durham et al., 2017). In addition, it has been reported that bone-borne MMD is a proven clinically stable surgical technique with stable long-term outcomes and without reported permanent TMJ symptoms (despite a significant increase in inter-condylar axes for bone-borne MMD in this study) (de Gijt et al., 2016).

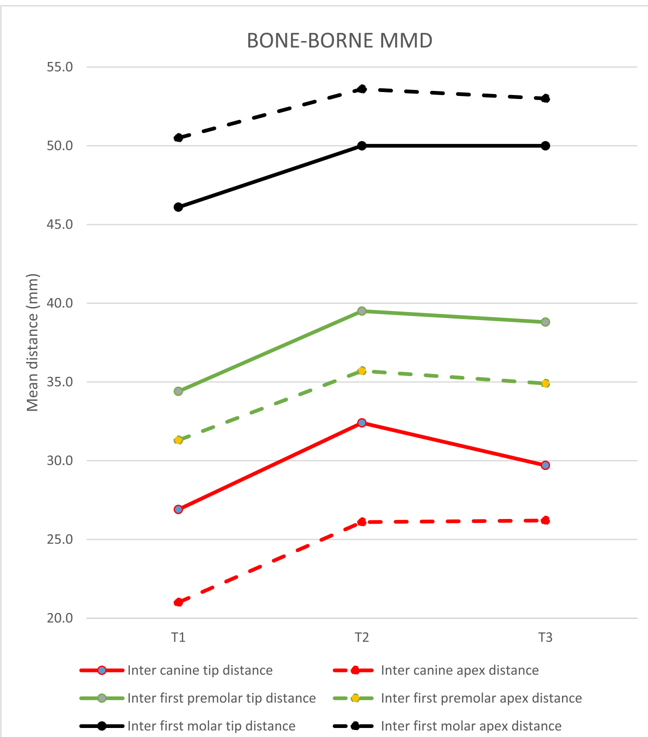
As of yet, based on the literature, this is the first clinical study comparing the dento-skeletal effects of bone-borne vs tooth-borne MMD using 3D imaging analysis techniques. Bone-borne MMD showed a more parallel-wise distraction gap at basal bone level, whereas tooth-borne MMD showed a V-shaped distraction gap. Both techniques showed stable dento-skeletal effects after 1 year post-operatively. Bone-borne and tooth-borne MMD seemed not to be superior to each other. Although bone-borne and tooth-borne MMD both are stable techniques to achieve transversal (dento-skeletal) expansion, the choice of distractor type is more dependent on anatomical and comfort factors. Bone-borne distractors are not recommended when there is insufficient buccal fold or tightness of the orbicularis oris increasing the risk for pressure ulcer. In addition, in patients with a deep overbite, bone-borne distractors may interfere with the upper incisors. Tooth-borne distractors show less hindrance compared to bone-borne distractors (Gül et al., 2021) and do not need a second surgical procedure for removal. However, a bone-borne distractor may be advantageous when MMD is planned in a patient with a healthy but reduced periodontium. Orthodontists and oral and maxillofacial surgeons should be aware of these (dento-skeletal) differences when choosing the distractor type.

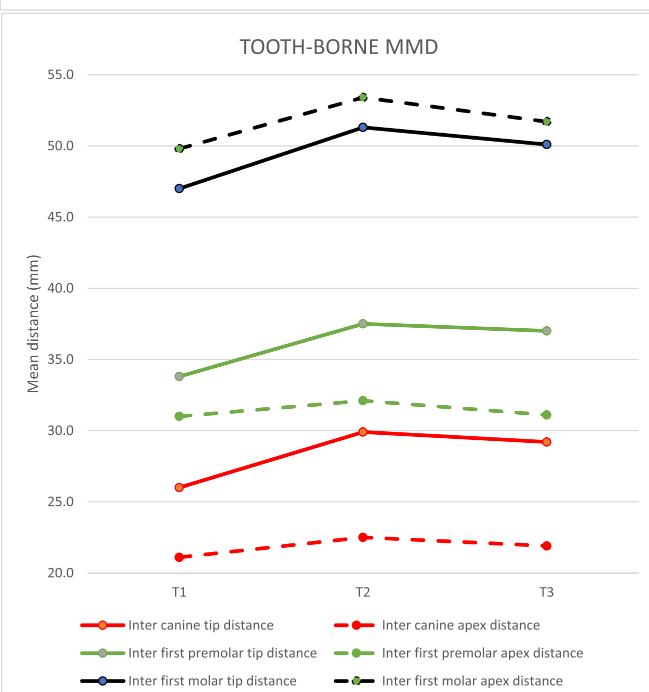
5. Conclusion

In conclusion, 3D CBCT analysis for dento-skeletal effects of bone-borne vs tooth-borne MMD and tooth-borne SARME showed stable dento-skeletal effects at 1 year post-operatively, indicating that they are reliable treatment options for transverse mandibular and maxillary discrepancies.

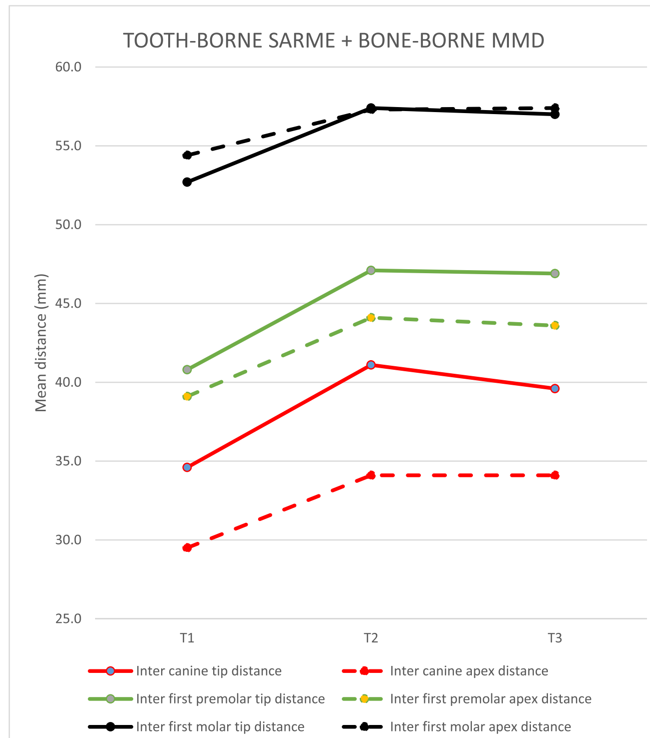
Bone-borne and tooth-borne MMD seemed not to be superior to each other. The choice of distractor type therefore depends more on anatomical and comfort factors. Orthodontists and oral and maxillofacial surgeons should be aware of these (dento-skeletal) differences when choosing the distractor type.

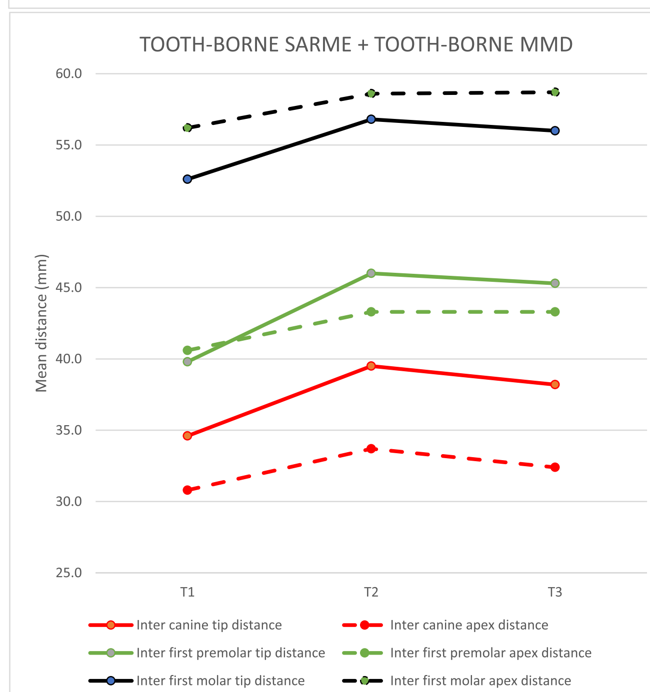
Appendix I. Bone-borne vs tooth-borne MMD, mean distance on tip and apex level



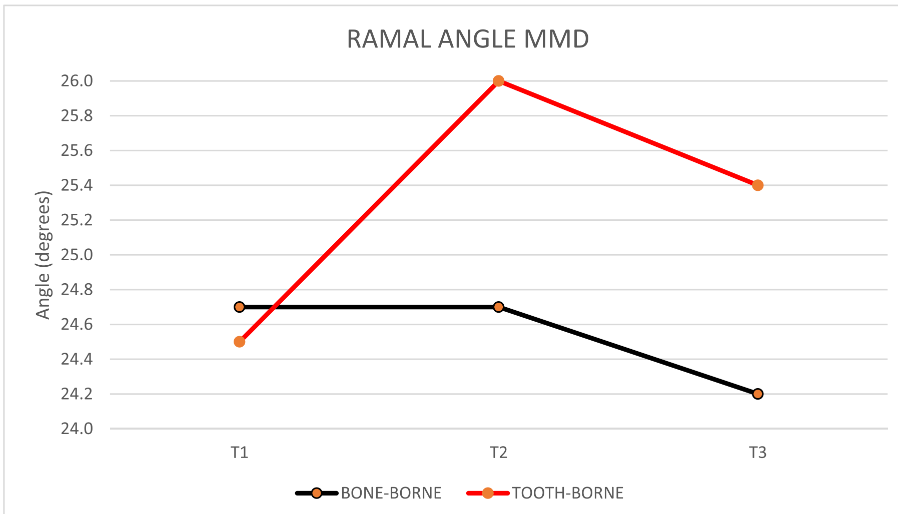


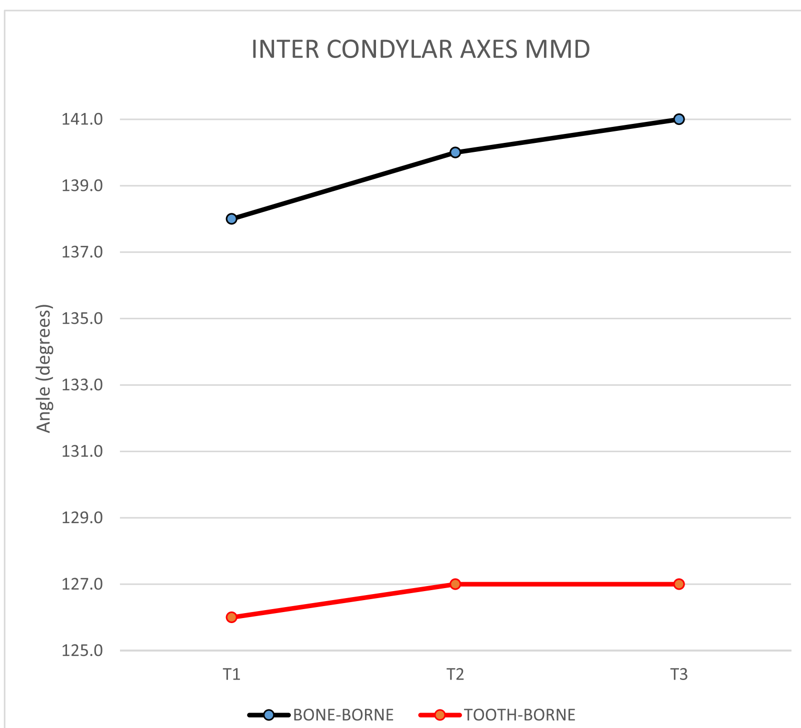
Appendix II. Tooth-borne SARME, mean distance on tip and apex level

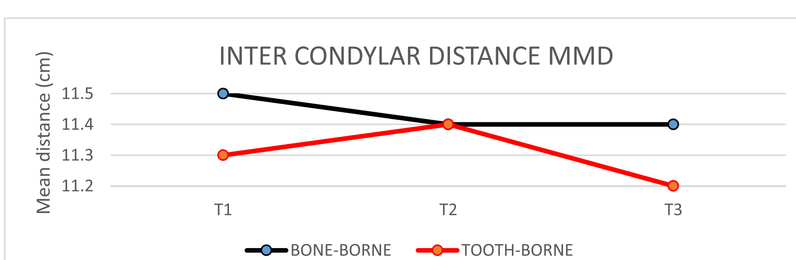




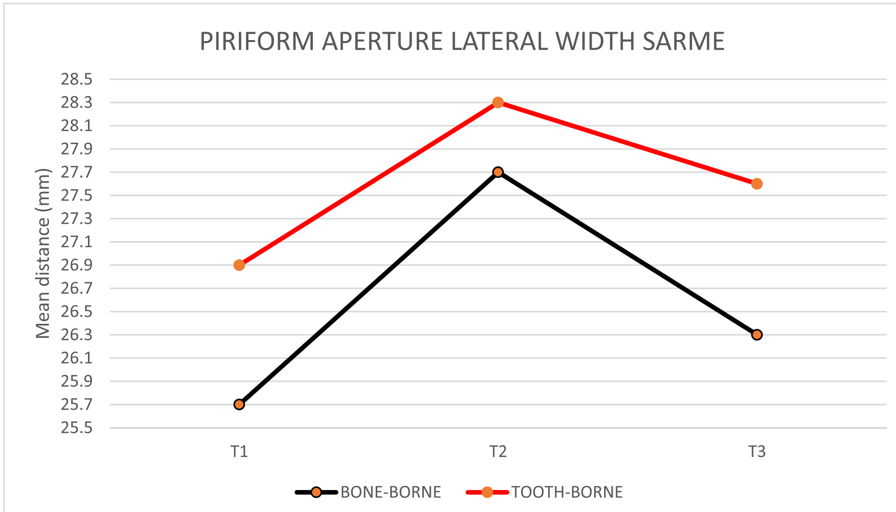
Appendix III. Bone-borne vs tooth-borne MMD, skeletal effects

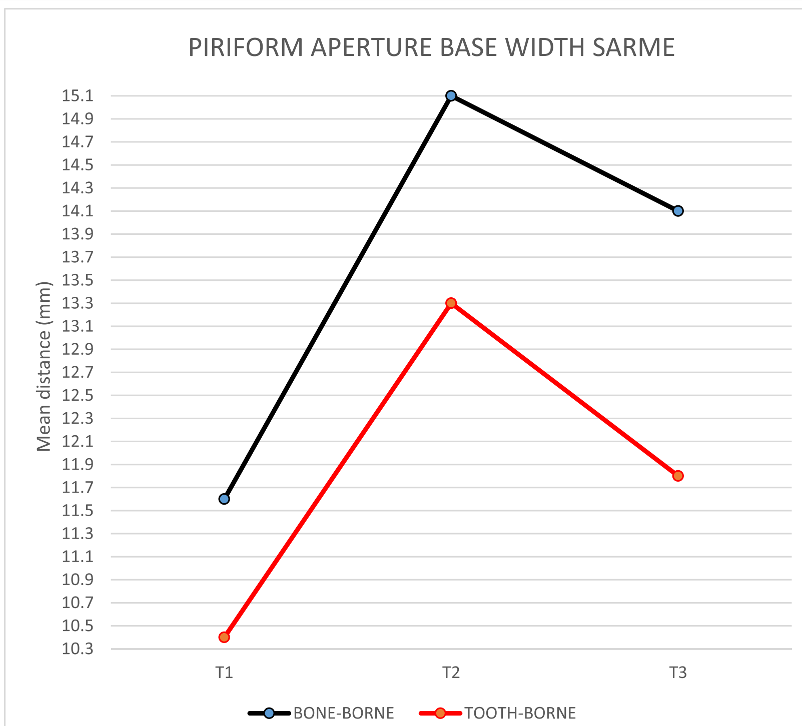






Appendix IV. Tooth-borne SARME, skeletal effects





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