Three-dimensional and clinical aspects of **BiM**axillary **Ex**pansion

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Three-dimensional and clinical aspects of **BiM**axillary **Ex**pansion

Driedimensionale en klinische aspecten van **BiM**axillaire **Ex**pansie

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Annem ve Babam için.

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General introduction

GENERAL INTRODUCTION

The growth of the mandible is different from that of the maxilla. The mandible (**Fig. 1**) is connected to the neurocranium on both sides by means of the temporomandibular joint (TMJ), which allows the mandible to perform rotational and translational movements. Growth of the mandible takes place by apposition and resorption of bone at the free surfaces. The main appositional areas are the superior surface of the alveolar process, and the posterior and superior surfaces of the ramus (**Fig. 2**)[1,2]. The mandibular symphysis is completely ossified around one year of age.

Fig. 1. The relation of the mandible (blue) to the neurocranium by means of the TMJ. The attachment of the maxilla (green) to the neurocranium (frontal and ethmoid) and viscerocranium (nasal, zygomatic, lacrimal, inferior nasal concha, palatine, vomer).

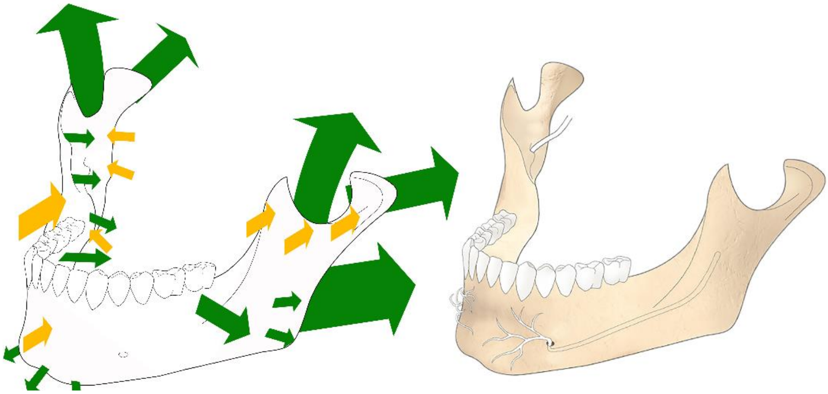

Fig. 2. Growth of the mandible takes place by apposition and resorption of bone at the free surfaces. *(This image was modified from* [1,2]*.)*

In contrast to the mandible, the maxilla (**Fig. 1**) is directly attached to the neurocranium (frontal and ethmoid) and viscerocranium (nasal, zygomatic, lacrimal, inferior nasal concha, palatine, vomer). The growth of the maxilla takes place at the oral plate and floor of the nasal cavity, as well as the nasal spine, as they grow downward and forward. Resorption of bone at superior surface of palate takes place at the same time with apposition at inferior surfaces of palate and alveolar processes resulting in forward and downward growth of nasal complex and maxilla in 'expanding V' manner. A downward and forward expansion of maxilla is the result of the growth in posterior area of maxilla (**Fig. 3**)[1,3].

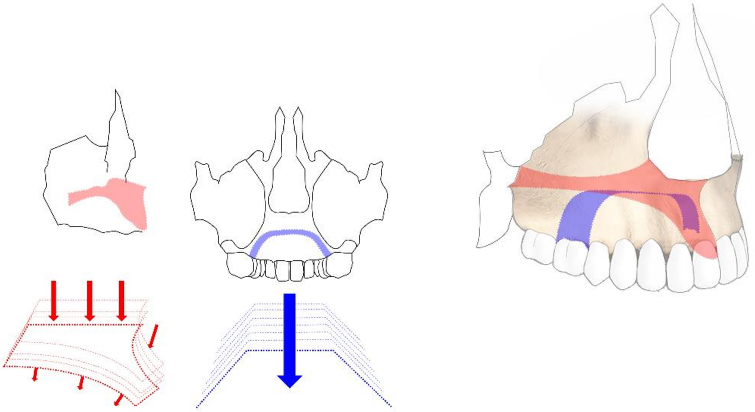

Fig. 3. Growth of the maxilla takes place at the oral plate and floor of the nasal cavity, as well as the nasal spine, as they grow downward and forward. *(This image was modified from [1,3].)*

The midpalatal suture between the left and right part of the maxilla closes around the age of 15 years and therefore can be expanded with orthodontic treatment until this age[4,5]. Posterior crossbite as a result of a transverse narrow maxilla is reported in 7.7% of the deciduous or mixed dentition patients, and this increases into the adulthood[6,7]. In the maxillofacial clinical field, transverse mandibular or maxillary hypoplasia are relatively common[8]. This hypoplasia can lead to transverse discrepancies due to the difference in total dental material and bony volume of the upper and lower arch. Transverse mandibular and maxillary discrepancies manifest in anterior and posterior crowding and can be prominent in patients with congenital deformities. Examples of congenital deformities that are well known to affect the transversal growth are cleft lip and palate, Treacher-Collins syndrome, Nager syndrome and syndromic craniosynostosis like Apert, Crouzon and Pfeiffer syndrome[9-11]. Examples of clinical impacts of transverse mandibular and maxillary discrepancies:

Buccal corridors (maxilla)
Crowding
Uni- or bilateral crossbite
Impacted anterior teeth with inadequate space and tipped teeth

Transverse mandibular and maxillary discrepancies were historically managed with orthodontic dental expansion and/or dental extraction therapy. Examples of appliances used for transverse discrepancies were the Schwarz and lip bumper appliance, lingual arches and functional appliances for the mandible. For the maxilla, these were the C-shaped spring, jackscrew appliance, all-wire frame with a non-spring-loaded jackscrew and Haas expander. Solitary dental expansion to correct mandibular and maxillary arch dimensions could lead to unstable post-treatment results with possible relapse as result of transverse skeletal discrepancies[12,13]. With these techniques, high relapse rates were observed on the long-term[14]. At 1 year of age the mandibular symphysis closes, making surgery necessary to achieve skeletal expansion[15,16]. Midpalatal suture expansion without surgery is possible until approximately the age of 15[4]. With the introduction of distraction for the facial skeleton in the early 1990s, new treatment options became possible[17,18].

DISTRACTION

In 1905 distraction was firstly described by Codivilla[19] and the first successful use of distraction on the femur of a significant group of patients was described in 1990[20]. In the early 1990s distraction was introduced for the facial skeleton and new treatment options became available in case the suture is already ossified or closed[13,17,18]. With this surgical technique, an osteotomy is performed, and a distractor is attached on both sides of it. With the activation of the distractor, both osteogenesis and histogenesis are induced.

Distraction osteogenesis is based on the fracture healing principle and consists of four phases:

I. Inflammation
II. Soft callus formation
III. Hard callus formation
IV. Remodelling

Regarding to this principle, at the end of inflammation phase distraction osteogenesis can be initiated which is around five to seven days after the osteotomy has been performed[21]. The gap between both sides of the osteotomy will increase gradually using a force perpendicular to the osteotomy. For this purpose, a distractor may be used, with discontinuous activation[22-24]. In general the applied distraction rate is about 0.5-1 mm per day spread over 2 moments.

After the desired lengthening or widening is reached, the distractor should be left to stabilize the osteotomy gap during the hard callus formation and remodelling to minimize the risk for pseudo arthrosis and relapse. For the facial skeleton this is usually around three months[25].

MANDIBULAR MIDLINE DISTRACTION

For widening of the mandible, the first distraction osteogenesis technique was described by Guerrero et al. in 1997[18]. Mandibular Midline Distraction (MMD) is used as a surgical technique to widen the mandible. The procedure is usually performed under general anesthesia. Distractors can be attached to the bone (bone-borne) during surgery, the teeth (tooth-borne) before surgery or a combination of both (hybrid) during surgery. After a horizontal incision is performed in the lower mucobuccal fold of the front region, the mucoperiosteum and mentalis muscles are reflected, and an osteotomy is performed in the midline of the mandible (**Fig. 4**).

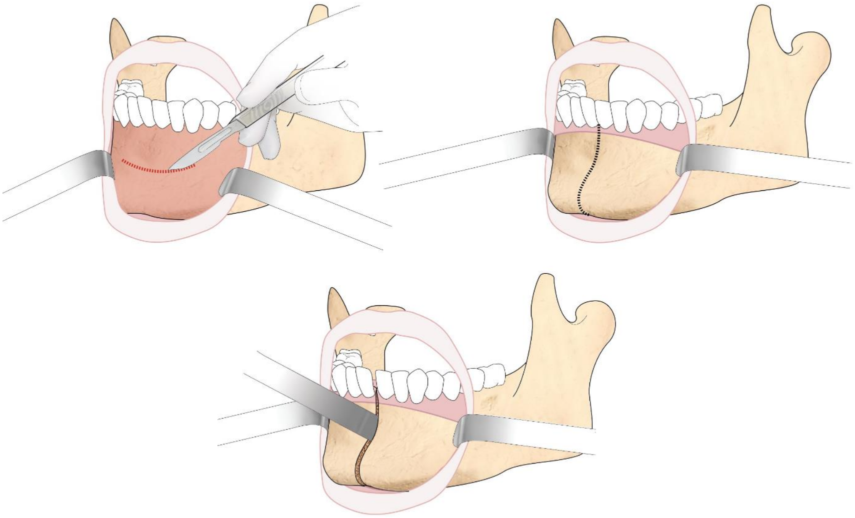

Fig. 4. MMD: After a horizontal incision is performed in the lower mucobuccal fold of the front region, the mucoperiosteum and mentalis muscles are reflected, and an osteotomy is performed in the midline of the mandible.

Subsequently, a (bone-borne) distractor is attached on both sides of the osteotomy. Following surgery, a latency period of five to seven days is respected to allow initial soft callus formation. The distractor is activated at a specific rhythm and rate, depending on the age of the patient, distraction site and preferences of the orthodontist or oral and maxillofacial surgeon (**Fig. 5**).

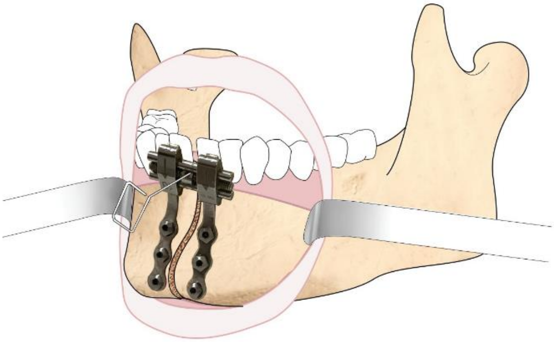

Fig. 5. MMD: Attachment of the (bone-borne) distractor and activation at a specific rhythm and rate.

After the desired expansion is reached, the distractor is left for three months to stabilize the distraction gap during the consolidation[26,27]. After this period, the distractor is removed. In contrast to the tooth-borne distractor, a second surgery is needed to remove the bone-borne or hybrid distractor.

Although MMD is a proven surgical technique to widen the mandible and to solve transverse mandibular discrepancies, long-term clinical outcomes are sparsely reported[28,29]. In addition, comparison of the outcomes of bone-borne and tooth-borne distractors is reported minimally[27,29]. In this thesis, the long-term outcomes and a dento-skeletal comparison of the bone-borne and tooth-borne distractor will be assessed for MMD.

For the mandible, the type and attachment of the distractor creates different vectors in three-dimensional (3D) planes since the TMJ is surrounded by soft tissue package and allows rotational, translational and horizontal movements. The biomechanical effects of the different type distractors may influence the distraction outcome and have their influence on the TMJ[26,30,31]. Theoretically, bone-borne distractors are more rigid allowing for more caudal widening in a parallel manner. This contrasts with tooth-borne distractors in which the forces are applied at the tooth level and thus more cranially, so that a dental tipping and skeletal tipping can occur of both hemi-mandibles. Until now research on dento-skeletal effects of bone-borne or tooth-borne MMD using 3D imaging analysis techniques has been reported scarcely[32-35], and is largely performed using conventional methods like dental cast models and posterior-anterior cephalograms[27-29,36]. In addition, 3D soft tissue effects of MMD have been reported minimally[34,37]. In this thesis the 3D dento-skeletal and soft tissue effects will be assessed for MMD.

From the clinical field, little is reported on experience, satisfaction and complications of MMD[38]. These aspects can be related to the technique and the type of distractor used. For example, the osteotomy technique may be related to the occurrence of tooth damage. Bone-borne distractors are positioned in the lower mucobuccal fold close to the mucosa of the lower lip, which could lead to pressure ulcers and discomfort. Due to the position of the bone-borne distractor and saliva with food accumulation, wound healing issues could occur. A second procedure, under local anesthesia or general anesthesia, is needed to remove the distractor. Tooth-borne distractors are positioned sublingually which could interfere with the tongue position and lead to discomfort. However, no second surgery is needed to remove the tooth-borne distractor.

These aspects are necessary for orthodontists and oral and maxillofacial surgeons to inform their patients properly. Patient experience and satisfaction, and complications following MMD will be evaluated in this thesis.

SURGICALLY ASSISTED RAPID MAXILLARY EXPANSION

For maxillary transverse discrepancies, Surgically Assisted Rapid Maxillary Expansion (SARME) is a well-known widely applied stable technique[25,39]. Clinically, indications for SARME include anterior or posterior crowding, uni- and bilateral crossbite, black buccal corridors, buccal tipping of the maxillary molars and lingual tipping of the mandibular molars[13,25,39].

Historically, the combination of surgery and orthodontic treatment for transverse expansion of the skeletally matured maxilla was introduced in 1938[13]. In 1999, the first bone-borne distractor was introduced by Mommaerts[40]. The already existing tooth-borne distractors would create more dental and skeletal tipping and thus more possible periodontal problems and relapse. Nevertheless, a prospective randomized open-label clinical study[25] has demonstrated no significant difference between bone-borne and tooth-borne SARME. The achieved widening at the dental level was stable at one year follow-up. In addition, tipping of the maxillary segments was equal. However, long-term clinical outcomes are minimally reported[41-43]. In this thesis, the long-term outcomes for SARME will be assessed.

In contrast to MMD, complications in SARME are well described[13,44]. In the literature, the most frequently mentioned complication is asymmetric expansion. A possible explanation for this could be the trend of minimal invasive surgery with transection of only the piriform aperture, the zygomatic buttress and the midpalatinal suture without transection of the pterygomaxillary junction. This theory is also supported by the outcomes of Carvalho et al. in their systematic review of complications for SARME[45]. Due to the anatomic relation, the transection between the piriform aperture and the zygomatic buttress is never completely horizontal on both sides of the median osteotomy. Therefore, expanding the maxilla may result in an asymmetric position in vertical direction. Other factors that could lead to an asymmetric expansion are broken or malfunctioning distractors. To add to the current knowledge, experiences and complications following SARME will be assessed from the clinical field of orthodontists and oral and maxillofacial surgeons in the Netherlands using a web-based survey.

Regarding experience and satisfaction from the patients' perspective, not much is reported in the literature[46,47]. Recently Baranto et al. reported the satisfaction outcomes using a self-made questionnaire on thirty patients who underwent SARME with a combined bone- and tooth-borne (hybrid) distractor. Twenty-nine of these thirty patients were satisfied with this treatment and had no regrets. Other preoperative difficulties like biting, chewing, dental position, facial appearance, speech and self-esteem had improved with this treatment according to most of the patients. Worsening of pain in the TMJ region was uncommon among the patients (6.7%)[48]. In this thesis, patient experience and satisfaction following SARME will be assessed.

BIMAXILLARY EXPANSION

In contrast to MMD, SARME is well reported using 3D imaging analysis techniques[49-55], regarding dento-skeletal and overlying soft tissues effects. However only one paper reported on dento-skeletal and overlying soft tissues effects of the combination of MMD and SARME, which is termed BiMaxillary Expansion (BiMEx), with the use of 3D imaging analysis techniques[34]. To our knowledge 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. These effects will be assessed for BiMEx in this thesis.

Among surgeons active in the maxillofacial field, there is still no consensus regarding the current practice for transverse mandibular and maxillary discrepancies. In contrast to distraction technique for the long bones[20,56], there is no standardized protocol for MMD and SARME. In the literature, there are many variable factors like the clinical indication, anesthesia technique, osteotomy technique (MMD: vertical or step, SARME: surgical transections), latency period, distractor type, distraction rate, overcorrection and consolidation period. These aspects are necessary for orthodontists and oral and maxillofacial surgeons to align and improve the treatment modalities for transverse mandibular and maxillary discrepancies and inform their patients better about the possible treatment options. The current practice for transverse mandibular and maxillary discrepancies from the point of orthodontists and oral and maxillofacial surgeons in the Netherlands, will be evaluated using a web-based survey in this thesis.

MINISCREW-ASSISTED RAPID MAXILLARY EXPANSION

Following the trend of minimal invasive surgery, a new technique is introduced to solve maxillary transverse discrepancies named Miniscrew-Assisted Rapid Maxillary Expansion (MARME)[57,58]. This is a technique, performed under local anesthesia without osteotomies. Two to four miniscrews are incorporated into a rapid maxillary expansion (RME) distractor which is fixated to the palatal bone (hybrid) (**Fig. 6-7**). With activation, forces are directly delivered on the basal bone through the miniscrews in an attempt to open the midpalatal suture in the skeletally matured maxilla (**Fig. 7**). The first reports show promising stable results, but mainly young non-syndromic patients are involved[59,60]. In this thesis, the current knowledge on MARME as a non-surgical maxillary expansion modality in skeletally mature patients will be assessed in a systematic review of the current literature. In addition, the primary objective is to assess dental, skeletal, upper airway and soft tissue effects. The secondary objective is to assess patient experience and satisfaction, and complications following MARME.

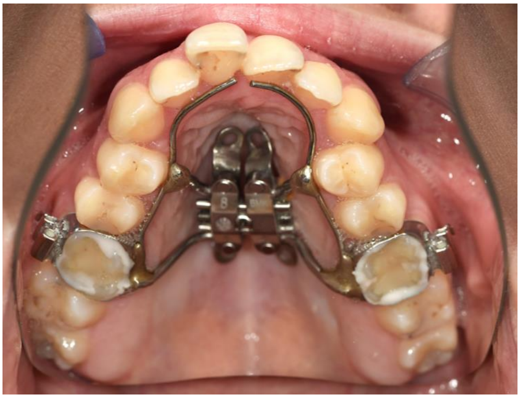

Fig. 6. MARME: Attachment of the RME distractor before screw fixation and activation.
(Clinical intra-oral photograph of a MARME patient from our own outpatient clinic.)

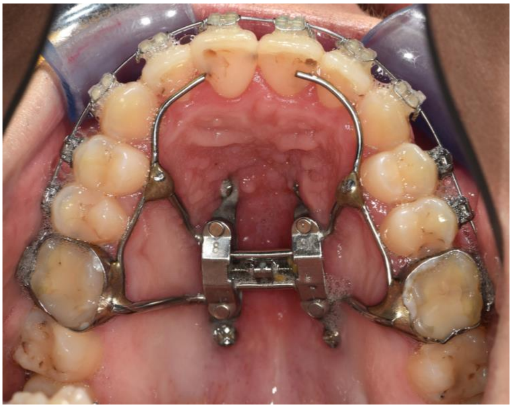

Fig. 7. MARME: Attachment of the RME distractor after screw fixation and activation.
(Clinical intra-oral photograph of a MARME patient from our own outpatient clinic.)

GENERAL AIM AND OUTLINE OF THIS THESIS

In this thesis, a systematic review is provided in *Chapter 2* concerning the 3D evaluation of MMD. *Chapter 3* provides the current evidence for MARME as a non-surgical maxillary expansion modality in skeletally mature patients in a systematic review of the current literature.

The general aim of this thesis is to assess the 3D dento-skeletal and soft tissue effects of BiMEx and these will be outlined in *Chapter 4* and *Chapter 5*.

MMD and SARME are both effective treatment modalities to solve transverse mandibular and maxillary discrepancies, however the long-term clinical outcomes are reported sparsely. Therefore, in *Chapter 6* and *Chapter 7* the long-term dento-skeletal effects of MMD and SARME will be provided. Additionally, to the general aim, the next aspects will be highlighted:

- *Chapter 8* presents the patient experience and satisfaction following MMD and SARME.
- *Chapter 9* shows the results of a web-based survey on the current practice for transverse mandibular and maxillary discrepancies among orthodontists and oral and maxillofacial surgeons in the Netherlands.
- *Chapter 10* provides an overview of our reported complications following bone-borne MMD using the Clavien-Dindo complication classification system.

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Three-dimensional evaluation of mandibular midline distraction: A systematic review

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ABSTRACT

To provide a literature overview on mandibular midline distraction (MMD) using three-dimensional (3D) imaging analysis techniques. Regarding different distractor types, the focus lies on changes in position and/or morphology of mandibular condyle and temporomandibular joint (TMJ), skeletal effects, dental effects, soft tissue effects and biomechanical and masticatory effects specifically on mandible and TMJ. According to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines, studies were included until March 27th 2017 from: Embase, Medline OvidSP, Web-of-science, Scopus, Cochrane and Google Scholar. Thirty-one full-text papers were assessed for eligibility and 15 met inclusion criteria: prospective (2), retrospective (2), case-report (1) and computational analysis (10). All included studies were graded low (level 4-5) on quality of evidence using Oxford Centre for Evidence-Based Medicine criteria. Limited amount of studies is available with low level of evidence and small sample sizes. Bone-borne distractor seems preferable when taking skeletal effects into account. Tooth-borne distraction leads to significant dental tipping. Hybrid distractor combined with parasymphyseal step osteotomy seemed to be most stable under functional masticatory loads. Effect of chewing appeared to be marginal during latency period. No permanent TMJ symptoms were reported and little is known about soft tissue effects.

SYSTEMATIC REVIEW REGISTRATION

International Prospective Register of Systematic Reviews, PROSPERO CRD42014010010.

INTRODUCTION

Transverse mandibular and maxillary discrepancies manifest in anterior and posterior crowding, and can be prominent in patients with developmental disorders and congenital deformities (e.g. Treacher-Collins, Apert, Crouzon, Nager). Traditionally, transverse discrepancies were treated with orthodontic appliances and/or tooth extractions. However, in the early 90s of last century distraction was introduced for the facial skeleton and new treatment options became available (McCarthy et al., 1992; Guerrero et al., 1997; Koudstaal et al., 2005). With this technique, both osteogenesis and histogenesis are induced.

Mandibular midline distraction (MMD) is used as a surgical technique to widen the mandible. An osteotomy is performed in the midline of the mandible and a distractor is attached on both sides of the osteotomy. Distractors can be attached to the bone (bone-borne), the teeth (tooth-borne) or a combination of both (hybrid). Following surgery, a latency period of 5-7 days is respected to allow initial soft callus formation. The distractor is activated at a specific rhythm and rate, depending on the distraction site and preferences of the surgeon or orthodontist. Indications for MMD are mandibular anterior or posterior crowding (Guerrero et al., 1997), uni- and bilateral crossbite (King et al., 2004), v-shape of the mandible, severe (maxillary-) mandibular transverse deficiency and impacted anterior teeth with inadequate space and tipped teeth (Proffit et al., 2003). In specific cases both the maxilla and the mandible need widening and bimaxillary expansion (BiMEx) is indicated. BiMEx is a combination of surgically assisted rapid maxillary expansion (SARME) and MMD (Weil et al., 1997; Del Santo et al., 2000; De Gijt et al., 2012).

The mandible is a curved bone which on both sides terminates at the temporomandibular joint (TMJ). The TMJ is surrounded by a soft tissue envelope and allows the mandible to perform rotational, translational and horizontal movements. The attachment and activation of the distractor creates different vectors in three-dimensional (3D) planes. The biomechanical properties of the distractors themselves are important as they may influence the outcome of distraction in the long-term and have their respective influence on the TMJ (Mommaerts, 2001; Conley and Legan, 2003; Mommaerts et al., 2005; Gunbay et al., 2009).

At present, research on MMD focused largely on conventional research methods including dental cast models and posterior-anterior cephalograms (De Gijt et al., 2012). However, imaging techniques and software have become more sophisticated. This makes it possible to analyse bony and soft tissue structures more accurately. In addition, in contrast to conventional radiographs, it is possible to perform 3D measurements of bony and soft tissue structures on 3D reconstruction models using cone beam computed tomography (CBCT). This technique has less radiation exposure than the multislice computed tomography (MSCT) with highly realistic facial and skeletal information when comparing with the 2D radiographs. Finite element method (FEM) studies can analyse stress distribution during MMD in the mandible and the TMJ.

The main objective of this study is to provide a literature overview on MMD using 3D imaging analysis techniques. Regarding different distractor types, the focus lies on the changes in position and/or morphology of mandibular condyle and TMJ, skeletal effects, dental effects, soft tissue effects and biomechanical and masticatory effects specifically on the mandible and the TMJ.

METHODS

Protocol and registration

The methods of the analysis were described and registered as a protocol in the International Prospective Register of Systematic Reviews (PROSPERO) under the number of registration: CRD42014010010. The Medical Ethics Committee of Erasmus MC, University Medical Center Rotterdam, the Netherlands approved the research protocol (approval number: MEC-2014-343).

Search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used as a guideline for this systematic review (Moher et al., 2009). An electronic search was performed with the following electronic databases until March 27th 2017:

- Embase;
- Medline OvidSP;
- Web-of-science;
- Scopus;
- Cochrane;
- Google Scholar.

The search strategy was conducted with defined combination in keywords specified for each of above databases *(Appendix I)*. References of included studies were hand-searched for other relevant studies to complete the search.

Inclusion criteria

Randomized controlled trials (RCT), controlled clinical trials (CCT), case series and finite element method (FEM) studies were included in this review. Adolescent- or adult-aged subjects who underwent a MMD, all types of distractors (bone-, tooth-borne or bone-and-tooth borne hybrid distractors) and all types of 3D imaging analysis techniques were included. The search strategy was restricted to English publications and animal studies were excluded. There was no restriction of sample size and follow-up period in the case series.

Data extraction and analysis

After performing the search strategy, all duplicates were removed. Two authors independently (AG and JPG) made a selection based on title and abstract when available. Papers were excluded if the study groups included congenital (craniofacial) deformities, mental retardation and history of radiation therapy in the area of interest. If the paper appeared to match with the inclusion criteria or when the abstract was lacking information or missing, the full-text paper was obtained. The selection of the full-text papers was then completely reviewed independently by both authors in accordance with all the inclusion criteria and then included or rejected. Included studies were graded on quality of evidence using the Oxford Centre for Evidence-Based Medicine (OCEBM) criteria (OCEBM, 2011). The included studies were scored on the origin of the study, study design, sample size, age range, gender, length of follow-up, 3D imaging analysis technique, 3D imaging software, type of osteotomy, type of distractor, latency period, distraction rate/gap, consolidation period and treatment outcome *(Table 1)*.

Table 1. Included studies.

Author	Year	Title	Origin	OCEBM level of evidence	Study design	3D imaging analysis technique
Bianchi et al.	2017	Soft, hard-tissues and pharyngeal airway volume changes following maxillo-mandibular transverse osteodistraction: Computed tomography and three-dimensional laser scanner evaluation	Italy	4	Prospective CS	CT, facial scan
Singh et al.	2016	Biomechanical Effects of Novel Osteotomy Approaches on Mandibular Expansion: A Three-Dimensional Finite Element Analysis	China	5	Computational study	FEM

Table 1. Included studies. (continued)

Author	Year	Title	Origin	OCEBM level of evidence	Study design	3D imaging analysis technique
Savoldelli et al.	2012	Comparison of stress distribution in the temporomandibular joint during jaw closing before and after symphyseal distraction: a finite element study	France	5	Computational study	FEM
Kim et al.	2012	A finite element study on the effects of midsymphyseal distraction osteogenesis on the mandible and articular disc	South Korea	5	Computational study	FEM
Boccaccio et al.	2011	Analysis of the performance of different orthodontic devices for mandibular symphyseal distraction osteogenesis	Italy	5	Computational study	FEM
Seeberger et al.	2011	Changes in the mandibular and dento-alveolar structures by the use of tooth borne mandibular symphyseal distraction devices	Germany	4	Retrospective CS	CT
Gunbay et al.	2009	Effects of transmandibular symphyseal distraction on teeth, bone, and temporomandibular joint	Turkey	4	Retrospective CS	CT
Landes et al.	2008	Prospective changes to condylar position in symphyseal distraction osteogenesis	Germany	4	Prospective CS	(3D)CT
Boccaccio et al. *a*	2008	Effects of aging on the latency period in mandibular distraction osteogenesis: a computational mechanobiological analysis	Italy	5	Computational study	FEM
Boccaccio et al. *b*	2008	Tissue differentiation and bone regeneration in an osteotomized mandible: a computational analysis of the latency period	Italy	5	Computational study	FEM
Gökalp	2008	Effects of symphyseal distraction osteogenesis on the temporomandibular joint seen with magnetic resonance imaging and computerized tomography	Turkey	4	Case report	MSCT, MRI

Table 1. Included studies. (continued)

Author	Year	Title	Origin	OCEBM level of evidence	Study design	3D imaging analysis technique
Boccaccio et al. *c*	2008	Comparison of different orthodontic devices for mandibular symphyseal distraction osteogenesis: a finite element study	Italy	5	Computational study	FEM
Boccaccio et al.	2007	The influence of expansion rates on mandibular distraction osteogenesis: a computational analysis	Italy	5	Computational study	FEM
Boccaccio et al.	2006	Mechanical behavior of an osteotomized mandible with distraction orthodontic devices	Italy	5	Computational study	FEM
Basciftci et al.	2004	Biomechanical evaluation of mandibular midline distraction osteogenesis by using the finite element method	Turkey	5	Computational study	FEM

Abbreviations: 3D, three-dimensional; CS, case series; CT, computed tomography; FEM, finite element method; MRI, magnetic resonance imaging; MSCT, multislice computed tomography; OCEBM, Oxford Centre for Evidence-Based Medicine.

The included studies were divided into two main groups, i.e. a ‘clinical’ (morphological) group and a ‘FEM’ (biomechanical) group. The objective of the ‘clinical’ group was to evaluate whether MMD provokes changes in position and/or morphology of mandibular condyle and TMJ, skeletal effects, dental effects, soft tissue effects by using 3D imaging analysis techniques. The objective of the ‘FEM’ group was to evaluate the distraction, masticatory effects and latency period, stress distribution and displacement of mandibular segments following MMD by using FEM.

RESULTS

The search results of the electronic databases yielded 757 citations (Embase, 148; Medline OvidSP, 144; Web-of-science, 130; Scopus, 197; Cochrane, 3 and Google Scholar 135). After correction for duplicates, 330 citations remained. Four papers were identified through reference list by hand-search.

All of the 334 papers were screened by title and abstract. 303 papers were excluded for different reasons, including papers with other topics than MMD; MMD, but not analysed by 3D imaging analysis techniques; and animal studies. The remaining 31 papers were screened based on the full-text paper. Of this selection another 16 papers were excluded for different reasons, including papers with other topics than MMD; not analysed by 3D imaging analysis techniques; animal studies; non-English-language papers; and presentations of meetings. A total of 15 studies were included *(***Fig. 1***; Table 1)*. Of this selection, only 5 studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017) met the OCEBM criteria for level 4 evidence as case series. The remaining 10 studies (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016) met the OCEBM criteria for level 5 evidence as mechanism-based reasoning *(Table 1)*.

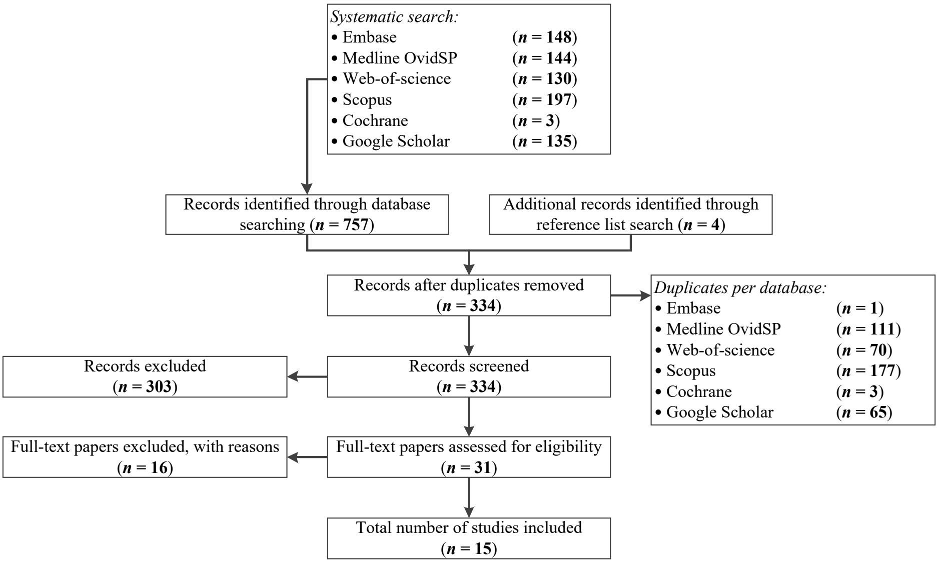

Fig. 1. Data extraction flowchart, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

Clinical group

This group consists of five studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017). In this group, the age of all the patients (*n* = 55) ranged from 14.3 to 43 years (32 female, 23 male), with a mean age of 21.9 years. The follow-up period depended on the objective of the study and ranged from 3 months (Landes et al., 2008; Seeberger et al., 2011) post-operatively to 48 months (Gunbay et al., 2009; Bianchi et al., 2017) post-consolidaton *(Table 2)*.

Table 2. Patient characteristics of included studies in the 'clinical group'.

Author	Year	Study design	3D imaging analysis technique	Sample size (*n*)	Age range, mean (years)	Gender (F/M)	Follow-up period (months)
Bianchi et al.	2017	Prospective CS	CT, facial scan	19	18-36, 26.3	11/8	24-48
Seeberger et al.	2011	Retrospective CS	CT	19	15-43, 27.1	12/7	3
Gunbay et al.	2009	Retrospective CS	CT	7	14.3-22.5, 16.2	3/4	36-48
Landes et al.	2008	Prospective CS	(3D)CT	9	15-43, 24.7	5/4	3-24
Gökalp	2008	Case report	MSCT, MRI	1	15, 15	1/-	6

Abbreviations: 3D, three-dimensional; CS, case series; CT, computed tomography; MRI, magnetic resonance imaging; MSCT, multislice computed tomography.

Surgical intervention and distraction

In 4 studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011) a midsymphyseal osteotomy was performed between the mandibular central incisors. A step osteotomy between the canine and lateral incisor was performed in 1 study (Bianchi et al., 2017). Bone-borne, tooth-borne and hybrid distractors were used. SARME was performed simultaneously in 4 studies (Landes et al., 2008; Gökalp, 2008; Seeberger et al., 2011; Bianchi et al., 2017). See further *Table 3* for additional baseline information of the studies.

Table 3. Surgical intervention and distraction in the 'clinical group'.

Author	Year	Osteotomy, anaesthesia	Distractor type	Latency period (days)	Distraction rate (mm/ days)	Consolidation period (months)	Additional surgery
Bianchi et al.	2017	Step MSO, GA	Bone-borne	7	1	2	SARME
Seeberger et al.	2011	Vertical MSO, ND	Tooth-borne	7	0.4	3	SARME
Gunbay et al.	2009	Vertical MSO, LA	Bone-borne	7	1	1	-
Landes et al.	2008	Step MSO, GA	Bone-borne	5	0.6	3	SARME
Gökalp	2008	Vertical MSO, GA	Tooth-borne	5	1	6	SARME

Abbreviations: GA, general anaesthesia; LA, local anaesthesia; MSO, midsymphyseal osteotomy; ND, not described; SARME, surgically assisted rapid maxillary expansion.

3D imaging analysis method

The following 3D imaging techniques were reported: 3D computed tomography (3DCT) (Landes et al., 2008), computed tomography (CT) (Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017), MSCT (Gökalp, 2008), magnetic resonance imaging (MRI) (Gökalp, 2008) and facial scan (Bianchi et al., 2017). These scans were performed pre-operatively in all studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017), at end of distraction (Gunbay et al., 2009), after completion of postoperative orthodontic treatment (Bianchi et al., 2017) and postoperatively at 3 months (Landes et al., 2008; Seeberger et al., 2011), at 6 months (Gökalp, 2008) and at 36 months (Gunbay et al., 2009).

There were various analysis methods applied for evaluating the mandibular condyle position. Most studies evaluated the mandibular condyle position by measuring the inter condylar distance (Landes et al., 2008; Gökalp, 2008; Bianchi et al., 2017), condylar axis (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009) and mandibular axis (Seeberger et al., 2011). Two studies analysed the TMJ region (Landes et al., 2008; Gökalp, 2008). Landes et al. measured lateral and inner distances from the condylar surface to the mandibular fossa on the coronal plane of (3D)CT scan (Landes et al., 2008). Landes et al., Seeberger et al. and Bianchi et al. measured the distance between the condyles (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017). Gökalp evaluated the disc positions of the condyle and the glenoid fossa on bilateral sagittal MRI scans in closed and open position of the mouth (Gökalp, 2008).

For evaluating skeletal effects, Seeberger et al. measured inter mental foramen distance and mandibular tilting (Seeberger et al., 2011). Bianchi et al. measured the distance of the genial tubercle to the hyoid bone, length of the hyoid bone to basal skull plane, mandibular body length, bigonial width, ramal angle and ramus length (Bianchi et al., 2017).

Evaluating the dental effects, inter first molar crown (Seeberger et al., 2011; Bianchi et al., 2017), inter first molar root (Seeberger et al., 2011; Bianchi et al., 2017), inter first premolar crown (Seeberger et al., 2011; Bianchi et al., 2017) and inter first premolar root distances were measured (Seeberger et al., 2011; Bianchi et al., 2017). These were measured by using the buccal cusps and the lingual root apices. Bianchi et al. added measurements of inter occlusal distances of the second molar, first molar, second premolar, first premolar and canine (Bianchi et al., 2017). Landes et al. measured the inter canine distance by using the dental cavum midpoint of the left and right inferior canine on the axial plane of the (3D)CT scan (Landes et al., 2008). Only Seeberger et al. performed measurements of first molar and first premolar angulation (Seeberger et al., 2011).

With regards to the soft tissue effects, Bianchi et al. examined morphological changes as shell-to-shell deviation (clearance vector map) and represented regional changes as a pseudo-colour map on the facial scan. Linear/angular measurements were performed using 17 landmarks taken from classical anthropometry and axial/sagittal cross sections were also obtained (Bianchi et al., 2017) *(Table 4)*.

Table 4. 3D imaging analysis method in the 'clinical group'.

Author	Year	3D imaging analysis technique	Period, phase	Reported analysis objects and methods
Bianchi et al.	2017	CT, facial scan	ND, pre-OP	Measurement of LMH, LHYO, GOGNR, GOGNL, ID, GOGO, RA°, ARGOR, ARGOL, IOSMD, IOFMD, IOSPMD, IOFPMD, IOCD, IFMCD, IFPMCD, IFMRD, IFPMRD on CT scan.
			ND, post-OP OT	Linear and angular measurements using 17 facial landmarks taken from classical anthropometry on facial scan.
Seeberger et al	2011	CT	1 week, pre-OP	Measurement of ID, IFMCD, IFPMCD, IFMRD, IFPMRD, FMA°, FPMA°, IMFD and MT° on 3D reconstruction of CT scan.
			3 months, post-OP	
Gunbay et al.	2009			
CT			ND, pre-OP	Measurement of DLRC° on CT scans.
			ND, end of distraction	
			36 months, post-OP	
Landes et al.	2008	(3D)CT	Same day, pre-OP	Measurement of ID, DLRC° and ICD on axial plane of (3D)CT scan.
			3 months, post-OP	Measurement of CSTFCD, CSTFLD and CSTFMD on coronal plane of (3D)CT scan.
Gökalp	2008	MSCT, MRI	ND, pre-OP	Measurement of PRMPC° on axial plane of MSCT scan.
			6 months, post-OP	Disc positions of condyle and glenoid fossa in closed and open position of the mouth evaluated on bilateral sagittal MRI scans of TMJ.

Abbreviations: 3D, three-dimensional; ARGOL, ramus length left; ARGOR, ramus length right; CSTFCD, condyle surface to fossa cranial distance; CSTFLD, condyle surface to fossa lateral distance; CSTFMD, condyle surface to fossa median distance; CT, computed tomography; DLRC°, distolateral rotation of condyle; FMA°, first molar angle; FPMA°, first premolar angle; GOGNL, mandibular body length left; GOGNR, mandibular body length right; GOGO, bigonial width; ICD, inter canine distance; ID, inter condylar distance; IFMCD, inter first molar crown distance; IFMRD, inter first molar root distance; IFPMCD, inter first premolar crown distance; IFPMRD, inter first premolar root distance; IMFD, inter mental foramen distance; IOCD, inter occlusal canine distance; IOFMD, inter occlusal first molar distance; IOFPMD, inter occlusal first premolar distance; IOSMD, inter occlusal second molar distance; IOSPMD, inter occlusal second premolar distance; LHYO, hyoid bone to basal skull plane length; LMH, genial tubercle to hyoid bone distance; MRI, magnetic resonance imaging; MSCT, multislice computed tomography; MT°, mandibular tilt; OP, operative; OT, orthodontic treatment; PRMPC°, posterolateral rotation of the medial pole of condyle; RA°, ramal angle; TMJ, temporomandibular joint.

Treatment outcome

In all cases the distraction was successful and the desired expansion was achieved. Regarding mandibular condylar position, a distolateral movement was found in two studies (Landes et al., 2008; Gunbay et al., 2009). This was between 2.5-3° in the study of Gunbay et al., where Landes et al. observed a distolateral movement of 0.028° (Landes et al., 2008; Gunbay et al., 2009). In the same study of Landes et al., the vertical lateral, cranial and median distances to the fossa remained unchanged with no angulation of the condyles in the coronal plane (Landes et al., 2008). Gökalp reported a bilateral posterolateral rotation of -1° (right) and -9° (left) of the medial pole of the condyles with an unchanged disc position of the TMJ (Gökalp, 2008). Lateral condylar displacement was analysed in three studies (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017). In the study of Seeberger et al. the intercondylar distance changed insignificantly for 0.67 ± 1.67 mm, while Landes et al. observed a significant mean decrease of -1.0 ± 0.1 mm (Landes et al., 2008; Seeberger et al., 2011). Bianchi et al. reported also a decrease for the intercondylar distance of -1.83 ± 0.11 mm, however this was not significant (Bianchi et al., 2017). There were only 3 cases of transient TMJ symptoms reported of all the patients in the 'clinical' group (Gunbay et al., 2009). No permanent TMJ symptoms are described.

With regards to the skeletal effects, Seeberger et al. observed a significant increase of the inter mental foramen distance and a significant tilting of the mandibular corpus with v-shaped rotation (Seeberger et al., 2011). Bianchi et al. reported a significant decrease of 21.43% for the genial tubercle of the mandible to the hyoid bone distance. The ramal angle decreased insignificantly and there was evidence of a slight increase of the mandibular body length (Bianchi et al., 2017).

Concerning dental effects, Seeberger et al. observed a significant increase of the inter- first molar, inter- first premolar crown and root distance and a significant lateral angulation on the tooth-borne distractor fixation level of all first molars and premolars (Seeberger et al., 2011). Landes et al. observed a significant increase in inter canine distance of 3.8 ± 0.18 mm (Landes et al., 2008). Bianchi et al. reported a significant increase in inter canine distance of 4.89 ± 1.96 mm, inter first premolar distance of 5.48 ± 1.89 mm and inter second premolar distance of 4.69 ± 3.78 mm. There was no significant increase for the inter molar distances. The mean expansion at the level of the root apices of the first premolars was 3.01 ± 0.83 mm and of the first molars was 3.35 ± 1.11 mm, which were both significant (Bianchi et al., 2017).

Evaluating the soft tissue effects for MMD, Bianchi et al. observed major post-operative changes in the lower lip and chin. MMD did not cause any vertical or horizontal asymmetry. There was statistical significance demonstrated in the sagittal projection of the cheilion, labialis inferior, pogonion points and enlargement of the mouth and chin. The axial sections through pogonion showed a forward displacement of the chin with enlargement after MMD *(Table 5)*.

Table 5. Treatment outcome in the ‘clinical group’.

Author	Year	3D imaging analysis technique	Distractor type	Follow-up period (months)	Sample size (*n*)	Reported outcome changes (distance, mm; angle/rotation, °)	
Bianchi et al.	2017	CT, facial scan	Bone-borne	24-48	19	LMH:	-2.08 ± 0.07*
						LHYO:	0.13 ± 0.28
						GOGNR:	1.61 ± 0.63
						GOGNL:	1.81 ± 0.36
						ID:	-1.83 ± 0.11
						GOGO:	0.12 ± 0.23
						RA°:	-2.31 ± 0.61
						ARGOR:	0.21 ± 0.15
						ARGOL:	0.06 ± 0.25
						IOSMD:	2.15 ± 0.88
						IOFMD:	4.01 ± 1.33
						IOSPMD:	4.69 ± 3.78*
						IOFPMD:	5.48 ± 1.89*
						IOCD:	4.89 ± 1.96*
						IFMCD:	4.59 ± 1.94
						IFPMCD:	5.44 ± 1.61*
						IFMRD:	3.35 ± 1.11*
						IFPMRD:	3.01 ± 0.83*
						Major post-operative changes in the lower lip and chin.	
						No vertical or horizontal asymmetry.	
						Statistical significance in the sagittal projection of cheilion, labialis inferior, pogonion points and enlargement of mouth and chin.	
						Forward displacement of the chin with enlargement on axial sections through pogonion.	
Seeberger et al.	2011	CT	Tooth-borne	3	19	ID:	0.67 ± 1.67
						IFMCD:	4.9 ± 1.30*

Table 5. Treatment outcome in the ‘clinical group’. (continued)

Author	Year	3D imaging analysis technique	Distractor type	Follow-up period (months)	Sample size (*n*)	Reported outcome changes (distance, mm; angle/rotation, °)	
						IFPMCD:	4.83 ± 1.63*
						IFMRD:	2.60 ± 2.05*
						IFPMRD:	2.93 ± 1.84*
						FMA°:	2.63 ± 1.75*
						FPMA°:	3.32 ± 1.57*
						IMFD:	2.67 ± 1.18*
						MT°:	2.30 ± 1.97*
Gunbay et al.	2009	CT	Bone-borne	36-48	7	DLRC°:	2.5 – 3
						TMJS:	3 (transient)
Landes et al.	2008	(3D)CT	Bone-borne	3	9	ID:	-1.0 ± 1.1*
						DLRC°:	0.028 ± 4.34
						ICD:	3.8 ± 0.18*
						CSTFLD:	0.4 ± 0.5
						CSTFCD:	0.4 ± 0.5
						CSTFMD:	0.4 ± 0.3
Gökalp	2008	MSCT, MRI	Tooth-borne	6	1	PRMPC°:	-1° (right)
							-9° (left)

Abbreviations: *, significant $P < 0.05$; 3D, three-dimensional; ARGOL, ramus length left; ARGOR, ramus length right; CSTFCD, condyle surface to fossa cranial distance; CSTFLD, condyle surface to fossa lateral distance; CSTFMD, condyle surface to fossa median distance; CT, computed tomography; DLRC°, distolateral rotation of condyle; FMA°, first molar angle; FPMA°, first premolar angle; GOGNL, mandibular body length left; GOGNR, mandibular body length right; GOGO, bigonial width; ICD, inter canine distance; ID, inter condylar distance; IFMCD, inter first molar crown distance; IFMRD, inter first molar root distance; IFPMCD, inter first premolar crown distance; IFPMRD, inter first premolar root distance; IMFD, inter mental foramen distance; IOCD, inter occlusal canine distance; IOFMD, inter occlusal first molar distance; IOFPMD, inter occlusal first premolar distance; IOSMD, inter occlusal second molar distance; IOSPMD, inter occlusal second premolar distance; LHYO, hyoid bone to basal skull plane length; LMH, genial tubercle to hyoid bone distance; MRI, magnetic resonance imaging; MSCT, multislice computed tomography; MT°, mandibular tilt; OP, operative; OT, orthodontic treatment; PRMPC°, posterolateral rotation of the medial pole of condyle; RA°, ramal angle; TMJS, temporomandibular joint symptoms.

FEM group

This group consists of ten studies (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016).

Only three studies (Basciftci et al., 2004; Kim et al., 2012; Savoldelli et al., 2012) reported the origin of the geometric data for the FEM model, which were obtained from healthy volunteers. The age of these volunteers ($n = 3$, all male) ranged from 22 to 30 years, with a mean age of 26.3 years *(Table 6)*.

Table 6. Patient characteristics of included studies in the 'FEM group'.

Author	Year	Study design	3D imaging analysis technique	Sample size (n)	Age (years)	Gender (F/M)
Singh et al.	2016	Computational study	FEM	1	ND	ND
Savoldelli et al.	2012	Computational study	FEM	1	30	M
Kim et al.	2012	Computational study	FEM	1	27	M
Boccaccio et al.	2011	Computational study	FEM	1	ND	ND
Boccaccio et al. *a*	2008	Computational study	FEM	1	ND	ND
Boccaccio et al. *b*	2008	Computational study	FEM	1	ND	ND
Boccaccio et al. *c*	2008	Computational study	FEM	1	ND	ND
Boccaccio et al.	2007	Computational study	FEM	1	ND	ND
Boccaccio et al.	2006	Computational study	FEM	1	ND	ND
Basciftci et al.	2004	Computational study	FEM	1	22	M

Abbreviations: 3D, three-dimensional; FEM, finite element method; ND, not described.

Distraction

Various analysing methods were applied for evaluating the distraction. In 9 FEM simulations, a vertical midsymphyseal osteotomy was performed (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012). Only 1 FEM simulation performed three types of osteotomy, including a midsymphyseal, angulated midsymphyseal and parasymphyseal step osteotomy (Singh et al., 2016). Various types of distractors were analysed in these simulations, bone-borne (Basciftci et al., 2004; Boccaccio 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016), tooth-borne (Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Singh et al., 2016) and hybrid distractors (Basciftci et al., 2004; Boccaccio 2008c; Boccaccio et al., 2011; Kim et al., 2012; Singh et al., 2016). The simulated distraction gaps were 2 mm (Boccaccio 2008a, 2008b, 2008c), 6 mm (Boccaccio et al., 2006; Boccaccio et al., 2007), 7 mm (Boccaccio et al., 2011), 8 mm (Kim et al., 2012) and 10 mm (Basciftci et al., 2004; Savoldelli et al., 2012). Singh et al. performed a

6-day distraction period with a frequency of 1 distraction per day, however the size of the distraction gap was not described (Singh et al., 2016) *(Table 7)*.

Table 7. Distraction in the ‘FEM group’.

Author	Year	Osteotomy	Distraction gap (mm)	Distractor type	Masticatory loads in model
Singh et al.	2016	Vertical MSO	ND	Bone-borne	Yes
		Angulated MSO		Tooth-borne	Yes
		Parasymphyseal SO		Hybrid	Yes
Savoldelli et al.	2012	Vertical MSO	10	Bone-borne	Yes
Kim et al.	2012	Vertical MSO	8	Bone-borne	Yes
				Tooth-borne	Yes
				Hybrid	Yes
Boccaccio et al.	2011	Vertical MSO	7	Bone-borne	Yes
				Tooth-borne	Yes
				Hybrid	Yes
Boccaccio et al. *a*	2008	Vertical MSO	2	Tooth-borne	Yes
Boccaccio et al. *b*	2008	Vertical MSO	2	Tooth-borne	Yes
Boccaccio et al. *c*	2008	Vertical MSO	2	Bone-borne	Yes
				Tooth-borne	Yes
				Hybrid	Yes
Boccaccio et al.	2007	Vertical MSO	6	Tooth-borne	Yes
Boccaccio et al.	2006	Vertical MSO	6	Tooth-borne	Yes
Basciftci et al.	2004	Vertical MSO	10	Bone-borne	No
				Hybrid	No

Abbreviations: MSO, midsymphyseal osteotomy; ND, not described; SO, step osteotomy.

Masticatory effects and latency period

Boccaccio et al. showed that parasitic rotations of the mandible arms may counteract arch expansion due mastication forces. There was a significant effect of the mastication forces on the mechanical response with the tooth-borne distractor (Boccaccio et al., 2006). The same author observed that the hybrid distractor provided the most stable situation at the distraction gap. The tooth-borne distractor showed similar displacement, though it had less stability under mastication forces (Boccaccio et al., 2011). These findings are in line with Singh et al. who presented that the hybrid distractor combined with a parasymphyseal step osteotomy permits reduction in the parasitic rotations produced by mastication forces (Singh et al., 2016). In another study Boccaccio et al. showed that the mandibular arch displacements were less than 10% different from the distraction gap of the tooth-borne and hybrid distractors. The hybrid distractor was the most stable under mastication forces (Boccaccio 2008c). The same author simulated the effects of aging on the latency period before starting the distraction with a tooth-borne distractor. The results showed an optimal latency period duration of 5-6 days for young (up to 20 years old) patients, 7-8 days for adult (about 55 years old) patients and 9-10 days for the elder (more than 70 years old) patients. The mastication forces showed to have a rather marginally influence on this (Boccaccio 2008a). Related to this outcome, the same author simulated two different mastication loads in another study. There was a full mastication load and a mastication load reduced by 70%. The results showed that both intramembranous and endochondral ossification are predicted to occur for the full mastication loading in the osteotomized region, while for the reduced mastication loading firstly intramembranous ossification is predicted. The results showed bony bridges between both sides of the bone callus after a latency period of 7-8 days (Boccaccio 2008b). Concerning this outcome, the same author reported previously that lower distraction rate of 0.6 mm/day leads to greater amounts of bony bridging. Subsequently, it was reported that distraction rates higher than 1.2 mm/day could lead to low quality of bone callus (Boccaccio et al., 2007).

Stress distribution and displacement of mandibular segments

In all FEM simulations the distraction was successful and the desired expansion was achieved. Each mandibular segment showed a different pattern of stress distribution and displacement dependent on the type of distractor.

Area contiguous to the distractor

Only two studies (Basciftci et al., 2004; Kim et al., 2012) reported the stress distribution in the area contiguous to the distractor. Basciftci et al. observed low stress distribution using the bone-borne or hybrid distractor in the area contiguous to the distractor (Basciftci et al., 2004). Kim et al. however, observed high stress distribution using a bone-borne distractor in the same area (Kim et al., 2012).

Dental arch and alveolar process

In the study of Kim et al. the tooth-borne distractor showed most expansion at the dental arch, followed by the hybrid distractor and the bone-borne distractor. In comparison to the hybrid distractor and bone-borne distractor, the tooth-borne distractor showed high levels of stress distribution and displaced the alveolar process and basal bone area from incisor region to premolar region in a parallel way. However, the bone-borne distractor showed a decrease of lateral displacement from anterior to posterior part (Kim et al., 2012). This outcome is in concordance with Basciftci et al. who observed a nonparallel separation of the dentoalveolar complex from anterior to posterior part with the bone-borne distractor (Basciftci et al., 2004).

Boccaccio et al. reported that expansion on the dental arch appeared to be more significant for the tooth-borne distractor and hybrid distractor than for the bone-borne distractor (Boccaccio et al., 2011). This outcome is in line with Singh et al. who presented a maximum stress distribution on the root using the tooth-borne distractor with a parasymphyseal step osteotomy. The same author presented the amount of bone displacement in parasymphyseal step osteotomy using the hybrid distractor was maximum and consistent, including a significant increase of inter canine, inter premolar and inter molar distance (Singh et al., 2016).

Corpus, gonion and ramus

Basciftci et al. observed minimal displacement of the ramal and gonion regions using the bone-borne or hybrid distractor. There was a high stress distribution observed in the ramal region (Basciftci et al., 2004). In contrast to this outcome, Kim et al. observed a low stress distribution with the bone-borne distractor and a more evenly stress distribution with the hybrid distractor in the mandibular body and ramal region while the tooth-borne distractor showed a higher stress distribution (Kim et al., 2012).

Condyle and articular disc

Basciftci et al. observed the highest stress distribution below the condylar area using the bone-borne or hybrid distractor, while there was a minimal condylar displacement (Basciftci et al., 2004). This is in concordance with Kim et al., as they observed a high level of stress distribution with the bone-borne, tooth-borne and hybrid distractor in the condylar neck area with minimal condylar displacement. In the articular disc, the tooth-borne distractor showed the highest stress distribution followed by the hybrid and bone-borne distractor (Kim et al., 2012). In contrast to these outcomes, Savoldelli et al. observed a similar stress distribution on the condylar surfaces and in articular discs before and after MMD with the bone-borne distractor (Savoldelli et al., 2012).

DISCUSSION

This systematic review represents an overview of the literature on studies about MMD using 3D imaging analysis techniques. Unfortunately, no RCT's and CCT's were found. With the used inclusion criteria, 15 potentially relevant papers were found of which 5 clinical studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017) and 10 FEM studies (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016). Due the wide variety of the outcome variables, there was a restriction in reviewing the literature following the systematic method and a meta-analysis of the data was not possible. The majority of the reported studies are FEM models, leading to a low level of evidence (OCEBM, 2011). FEM models of human masticatory system are useful to identify and predict the stress distribution in the anatomical structures. However, the human mandible is not symmetric and there are many individual differences.

Changes in position and/or morphology of mandibular condyle and TMJ

The effect of MMD on the condyles and TMJ is closely related to the rigidity of the distractor. Due the different fixation points of the various types of distractors, each type of distractor causes a different amount of force with a different vector on the mandible, and thus on the condyle and the TMJ.

With regards to the condylar rotation, a distolateral rotation was found in two studies (Landes et al., 2008; Gunbay et al., 2009). An explanation for this finding might be that the intercondylar distance decreased in the study of Landes et al., and a distolateral rotation occurred. However, both authors used different distractors. Landes et al. used an axially high rigid distractor (The Modus, Medartis, Basel, Switzerland), while Gunbay et al. used an axially low rigid distractor (TMD, Surgi-Tec NV, Bruges, Belgium) which may have influenced the outcome. Furthermore, Landes et al. analysed the rotational movement after 3 months of consolidation and Gunbay et al. analysed directly following distraction not taking the adaptation of the condyles into account. Both analyses were performed using CT scans. There was an inconspicuous bilateral posterolateral rotation reported of the medial pole of the condyles on the axial CT plane with an unchanged disc position of the TMJ on the sagittal MRI plane (Gökalp, 2008). This rotation was asymmetrical and without clinical symptoms for the patient, indicating adaptability of the condyle. This outcome should be adopted cautiously considering this is a case-report with a short follow-up of 6 months.

Regarding intercondylar distance, both an increase and a decrease was found. Seeberger et al. observed an insignificant increase using a tooth-borne distractor, while Landes et al. observed a significant decrease and Bianchi et al. an insignificant decrease using a bone-borne distractor (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017). Theoretically, tooth-borne distractors exert their force mainly on a dentoalveolar level and create a combination of an increased vertical angle and more posterolateral widening when compared to bone-borne distractors, which exert their force anteriorly on basal bone level and would create anterolateral expansion. Based on this, tooth-borne distractors could lead to a greater lateral displacement of the posterior part of the mandible and increased intercondylar distance with an increase of stress distribution in the TMJ. However, Kim et al. observed minimal condylar displacement using a tooth-borne distractor with an increased stress distribution in the articular disc in a FEM study (Kim et al., 2012). The found decrease in intercondylar distance may be due the combination of the fixation points of the bone-borne distractor and the soft tissue envelope surrounding the posterior part of the mandible, TMJ especially. This soft tissue envelope could form sufficient resistance in the posterior part of the mandible, since bone-borne distractors practice their force anteriorly of the mandible. This is also supported by the high levels of stress distribution in the condylar area with minimal condylar displacement, observed by Basciftci et al. and Kim et al. with the bone-borne distractor in a FEM study (Basciftci et al., 2004; Kim et al., 2012). However, Basciftci et al. did not consider the mastication forces and soft tissues in the TMJ. Kim et al. did consider the mastication forces, and the analysis was only based on the left side of the mandible without taking into account the soft tissues in the TMJ. Since humans are not symmetrical, the conclusion must be interpreted with some care. In contradiction, Savoldelli et al. generated a FEM model with a complete masticatory system before and after MMD during jaw closing using a bone-borne distractor, including the soft tissues in the TMJ. There was a similar stress distribution observed on the condylar surfaces and in articular discs before and after MMD. Their study suggests that anatomical changes in TMJ should not predispose to long-term tissue fatigue. There was an absence of clinical permanent TMJ symptoms after MMD (Savoldelli et al., 2012). This is supported by Gunbay et al., who reported 3 transient cases of TMJ symptoms, which were all only mild TMJ pain and resolved after the distraction period (Gunbay et al., 2009). Overall, no permanent clinical TMJ symptoms were found in this systematic review. It can be assumed that MMD does not lead to clinical permanent TMJ symptoms. However, this assumption is mostly estimated by FEM studies and based on a small number of clinical studies with relative short follow-up periods and small sample sizes.

Skeletal effects

With regards to skeletal effects, there was a significant increase of the inter mental foramen distance and a significant tilting of the mandibular corpus with v-shaped rotation observed following MMD using a tooth-borne distractor (Seeberger et al., 2011). This outcome is in disagreement with the results of Kim et al., who observed a displacement of the alveolar process and basal bone area in a parallel way from incisor region to premolar region with a notable displacement on the ramus (Kim et al., 2012). However, this outcome is based on a FEM model with the described limitations. Bianchi et al. reported an insignificant decrease of the ramal angle and a significant decrease of 21.43% for the genial tubercle of the mandible to the hyoid bone distance (Bianchi et al., 2017). These findings were obtained using a bone-borne distractor.

Overall, bone-borne distractors cause a more proportionate expansion in vertical direction compared to the hybrid and tooth-borne distractors (Gunbay et al., 2009; Seeberger et al., 2011). Bone-borne distractors practice their force mostly at the mandibular basal level compared to tooth-borne distractors. This is in line with Kim et al. and Boccaccio et al., who observed more expansion at the alveolar process area and dental arch with the tooth-borne distractor compared to the hybrid and bone-borne distractor (Boccaccio et al., 2011; Kim et al., 2012).

These findings suggest that the bone-borne distractor is preferable regarding the skeletal effects. However, it should be noted that a second surgical procedure is needed to remove this distractor as compared to the tooth-borne distractor.

Dental effects

Three studies (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017) reported the inter dental distances following MMD. Landes et al. and Bianchi et al. showed a significant change of the inter canine distance. However, both authors used a different type of distractor (Landes et al., 2008; Bianchi et al., 2017). Seeberger et al. and Bianchi et al. measured both the inter first molar crown, inter first molar root, inter first premolar crown and inter first premolar root distances (Seeberger et al., 2011; Bianchi et al., 2017). Except the inter first molar crown distance in the study of Bianchi et al., all of these distances changed significantly in both studies (Seeberger et al., 2011; Bianchi et al., 2017). Both authors used a different type of distractor and Seeberger et al. reported a relatively short follow-up period of 3 months, which makes it difficult to compare (Seeberger et al., 2011; Bianchi et al., 2017). Longer follow-up periods are needed to analyse the dental stability taking relapse and remodelling into account. Concerning dental angulation, data is sparse due to different influencing factors like the type of distractor, widening of the hemi-mandible, orthodontic treatment and availability of 3D imaging analysis techniques. Only one study reported the dental angulation following MMD, which was a significant lateral angulation on the tooth-borne distractor fixation level of all first molars and premolars (2.63° and 3.32° respectively) (Seeberger et al., 2011). It can be concluded that the tooth-borne distractor leads to significant dental tipping, which could possibly affect the dental stability negatively in the long-term.

Soft tissue effects

Only one study (Bianchi et al., 2017) reported soft tissue effects following MMD. Major post-operative changes in the lower lip and chin were observed. MMD did not cause any vertical or horizontal asymmetry. There was statistical significance demonstrated in the sagittal projection of the cheilion, labialis inferior, pogonion points and enlargement of the mouth and chin. The axial sections through pogonion showed a forward displacement of the chin with enlargement after MMD. It should be considered that dental movements due orthodontic treatment may have an influence on these findings, especially for the lower lip projection. There was an insignificant increase of the mandibular body length, which could be an explanation for the chin projection. However, in this study simultaneous SARME was performed which complicates the interpretation of the soft tissue effects isolated for MMD. It can be assumed that MMD leads to soft tissue changes specifically for the lower lip and chin projection, but it should be noted that this assumption is only based on one study.

Biomechanical and masticatory effects specifically on the mandible and the TMJ

Biomechanical and masticatory effects together constitute an important role in MMD. The hybrid distractor seems to be the most stable under functional masticatory loads (Boccaccio et al., 2011), specifically combined with a parasymphyseal step osteotomy (Singh et al., 2016). The magnitude of these masticatory loads seems to have a rather marginally influence on the optimal latency period duration with the use of a tooth-borne distractor (Boccaccio 2008a). However, these masticatory loads can influence the bone callus formation in the distraction gap (Boccaccio 2008b), where high distraction rates could lead to low quality bone callus (Boccaccio et al., 2007). These outcomes could support healthcare professionals in their choice of distractor type and provide a safer control of the distraction. It can be assumed that the effect of chewing appeared to be marginal on the latency period. However, this assumption is based on FEM models with various distraction gaps. Moreover, not all FEM models take into account the complete in vivo situation including the masticatory loads and TMJ. This complicates the comparison of these outcomes. Mastication loads could be influenced by the possible strengthening of these masticatory muscles and dental contact between the maxilla and the mandible could influence these mastication loads. Also, MMD is often combined with SARME and there are no FEM models available simulating this situation.

CONCLUSION

A limited amount of studies is performed on MMD using 3D imaging analysis techniques. Most of these papers are FEM studies and characterized by a low level of evidence. Clinical studies on the (long-term) 3D biomechanical effects of MMD are sparse and with relatively small sample sizes. There is inconsistency between the effects and the clinical relevance of the distractor types. The bone-borne distractor seems preferable when taking skeletal effects into account. Tooth-borne distraction leads to significant dental tipping, theoretically increasing the risk of relapse. The hybrid distractor combined with a parasymphyseal step osteotomy seemed to be the most stable under functional masticatory loads. The effect of chewing appeared to be marginal during the latency period. From these studies, it can be concluded that MMD does not result in clinical permanent TMJ symptoms. However, possible long-term effects on the TMJ are not clarified yet since long-term follow-up studies are lacking. In addition, little is known about the soft tissue effects of MMD. More clinical studies with large case series are needed to clarify long-term morphologic 3D aspects of MMD by using 3D imaging analysis techniques.

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APPENDIX I. SEARCH STRATEGIES.

Embase

(‘distraction osteogenesis’/de OR (distract* NEAR/3 (osteogenes* OR midline)):ab,ti) AND (mandible/de OR ‘mandible osteotomy’/de OR ‘mandible condyle’/de OR chin/de OR (mandib* OR ‘lower jaw’ OR condyle* OR chin):ab,ti) AND (‘three dimensional imaging’/de OR (‘three dimensional’ OR 3d OR 3-d):ab,ti) NOT ([animals]/lim NOT [humans]/lim)

Medline OvidSP

(“Osteogenesis, Distraction”/ OR (distract* ADJ3 (osteogenes* OR midline)).ab,ti.) AND (exp mandible/ OR (mandib* OR “lower jaw” OR condyle* OR chin).ab,ti.) AND (exp “Imaging, Three-Dimensional”/ OR (“three dimensional” OR 3d OR 3-d).ab,ti.) NOT (exp animals/ NOT humans/)

Cochrane

((distract* NEAR/3 (osteogenes* OR midline)):ab,ti) AND ((mandib* OR ‘lower jaw’ OR condyle* OR chin):ab,ti) AND ((‘three dimensional’ OR 3d OR 3-d):ab,ti)

Web-of-science

TS=(((distract* NEAR/3 (osteogenes* OR midline))) AND ((mandib* OR “lower jaw” OR condyle* OR chin)) AND ((“three dimensional” OR 3d OR 3-d)) NOT ((animal? OR monkey? OR goat? OR dog? OR minipig? OR pig? OR swine? OR rat? OR sheep?) NOT (human? OR patient?)))

Scopus

TITLE-ABS-KEY(((distract* W/3 (osteogenes* OR midline))) AND ((mandib* OR “lower jaw” OR condyle* OR chin)) AND ((“three dimensional” OR 3d OR 3-d)) AND NOT ((animal? OR monkey? OR goat? OR dog? OR minipig? OR pig? OR swine? OR rat? OR sheep?) AND NOT (human? OR patient?)))

Google Scholar

“distraction osteogenesis”|”midline distraction” mandible|mandibular 3d|”3|three dimensional|d”

3

Mini-screw assisted rapid maxillary expansion: A systematic review

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ABSTRACT

Miniscrew-assisted rapid maxillary expansion (MARME) is an upcoming, nonsurgical technique for transverse maxillary expansion. This study aimed to evaluate current evidence on MARME performed in skeletally mature patients. Primarily, dental, skeletal, upper airway and soft tissue effects were assessed. Secondarily, patient experience and satisfaction, and complications were assessed. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines were used. An electronic search up to November 21st, 2021 was set up in Embase, Medline OvidSP, Web-of-science, Scopus, Cochrane, and Google Scholar. Additionally, hand searched references were considered for inclusion. One hundred and forty-two full text papers were assessed for eligibility, of which 32 studies met the inclusion criteria. Most included studies were graded as low level evidence on the Oxford Centre for Evidence-Based Medicine criteria. MARME seems effective for achieving adequate dental, skeletal and upper airway expansion in patients aged around 20 years. However, long-term outcomes and effects in older patients are limited. MARME induced paranasal soft tissue changes. Care should be taken in periodontally compromised patients and periodontal conditions should be monitored. Besides studies comparing MARME to surgically assisted rapid maxillary expansion (SARME), future studies should focus on complications, patient experience and satisfaction, and long-term outcomes.

SYSTEMATIC REVIEW REGISTRATION

This systematic review was registered as a protocol in the International Prospective Register of Systematic Reviews (PROSPERO CRD42020161461).

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INTRODUCTION

Transverse maxillary deficiencies can lead to anterior crowding and bilateral crossbites, which are common orthodontic problems[1-3]. Treatment of transverse maxillary deficiencies is required to achieve an adequate transverse maxillary dimension and a stable and functional occlusion[4]. Rapid maxillary expansion (RME) is an orthodontic technique which can be used to increase transverse maxillary and palatal dimensions, by expanding the midpalatal suture and inducing skeletal orthopaedic expansion[5,6]. However, around the age of 14 years, the midpalatal suture matures and interdigitation increases[7-10]. Consequently, in adults, the concept of orthodontic maxillary expansion remains controversial, as the high friction in the midpalatal suture could lead to alveolar bone bending, dental tipping, periodontal damage, unstable end results prone to relapse and limited expansion distance[8,11,12]. Therefore, surgically assisted rapid maxillary expansion (SARME) can be considered in skeletally mature patients. Based on the principle of distraction osteogenesis, SARME allows for gradual opening and expansion of the midpalatal suture by gradual widening. The technique involves buccal corticotomies following a LeFort I approach and a median osteotomy between the central incisors[13]. These osteotomies dispel the high resistance of the articulation between the bony palate, zygomatic and sphenoid bones. The distractors are typically placed before the procedure by the orthodontist and expansion forces ensure widening of the midpalatal suture[7,14,15]. Yet, the need for surgery under general anaesthesia and surgical risks such as bleeding and infections may make patients reluctant to undergo this procedure[16]. Furthermore, the surgical procedure is costly and requires hospitalization[12].

Miniscrew-assisted rapid maxillary expansion (MARME) is a technique in which miniscrews are incorporated into an RME device and is fixated to the palatal bone (**Fig. 1.**). This procedure is generally performed under local anaesthesia. RME forces are delivered directly on the basal bone through the miniscrews in an attempt to open the midpalatal suture. This potentially provides a nonsurgical alternative for transverse expansion of the maxilla in skeletally mature patients.

This systematic review was conducted to evaluate the current evidence for MARME as a nonsurgical maxillary expansion modality in skeletally mature patients. The primary objective was to assess dental, skeletal, upper airway and soft tissue effects. The secondary objective was to assess patient experience and satisfaction, and complications.

Figure 1. Intra-oral images of an MARME appliance in situ in unexpanded (upper) and expanded (lower) state.

METHODS

Protocol and registration

A systematic review on MARME was conducted. The analysis was registered as a protocol in the International Prospective Register of Systematic Reviews (PROSPERO CRD42020161461). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used as a guideline for this systematic review[17].

Search strategy

A systematic, computerized search strategy, using various combinations of relevant keywords was composed and performed on November 21st, 2021 (*Appendix*). The following databases were consulted: Embase, Medline OvidSP, Web-of-science, Scopus, Cochrane and Google Scholar.

In- and exclusion criteria

Randomized controlled trials (RCT), controlled clinical trials (CCT) and observational studies, with a sample size >5 were considered for inclusion in this review. Included patients were skeletally mature subjects who underwent nonsurgical maxillary expansion by means of a tooth and bone-borne MARME appliance. A minimum mean age of 14 years was applied. Studies on patients with a craniofacial deformity (including cleft palate), studies on animal or artificial models, preliminary studies, systematic reviews, conference abstracts, editorials, comments, book chapters and finite element (FE) studies were excluded. Moreover, studies using a solely bone-borne appliance were excluded, because of the different biomechanical effects compared to a tooth and bone-borne appliance. The language was restricted to English.

Study selection

After the electronic search, all duplicates were removed. Study selection on title and abstract was independently performed by the first two authors (KRRRM and AG). Independent selections were compared, and discrepancies were resolved by consensus. The full text of papers considered relevant after title and abstract screening was obtained and assessed independently by both authors. In case a full text paper could not be retrieved online, the corresponding author was contacted. Independent selections were compared, and a list of included studies was composed. References and citations of included studies were manually screened for additional relevant studies.

Data extraction and quality assessment

Data from the included studies on study origin, sample size, age and age range, gender distribution, follow-up length, type of MARME appliance, distraction protocol and outcome evaluation techniques were extracted (*Table 1, 2*). Included papers were graded on quality of evidence using the Oxford Centre for Evidence-Based Medicine (OCEBM) criteria[18].

RESULTS

The electronic database search resulted in 842 articles (Embase 226, Medline OvidSP 203, Web-of-Science 230, Cochrane 83, Google Scholar 100). Two articles were identified through reference list search. After removal of duplicates, 402 articles remained.

Title and abstract screening was performed for all 402 articles. Two hundred and sixty (260) articles were excluded on title and abstract screening for different reasons, including systematic reviews and meta-analyses, case reports, papers covering other topics than MARME, inclusion of cleft palate patients, not meeting the age restriction, applica-

Table 1. Study characteristics of included studies.

Author	Year	Origin	Inclusion period	Study design	OCEBM Level	Sample size (n)	Mean age, years (range or ± SD)	Sex, M/F	Follow-up
Abedini et al.	2018	United States[1]	-	Retrospective CS	4	25	21.3 (14.8 - 25.1)	9/16	1 year after expansion
Almaqrami et al.	2021	China[3]	-	Retrospective CS	4	49	23.9 ± 3.9	7/42	<3 weeks postexpansion
Bud et al.[a]	2021	Romania[6]	-	Retrospective CS	4	20	23.8 (21 - 35)	7/13	2 months postexpansion
Bud et al.[b]	2021	Romania[6]	-	Retrospective CS	4	27	24 (19 - 35)	9/18	2 months postexpansion
Calil et al.	2021	Paraguay/Brazil[7]	-	Retrospective CS	4	16	24.9 ± 7.6	5/11	6 months
Cantarella et al.	2017	United States[1]	-	Retrospective CS	4	15	17.2 (13.9 - 26.2)	6/9	5 ± 2 months
Cantarella et al.[a]	2018	United States[1]	-	Retrospective CS	4	15	17.2 (13.9 - 26.2)	6/9	5 ± 2 months
Cantarella et al.[b]	2018	United States[1]	-	Retrospective CS	4	15	17.2 (13.9 - 26.2)	6/9	5 ± 2 months
Choi et al.	2016	Korea[8]	2004-2010	Retrospective CS	4	20	20.9 (18 - 28)	10/10	51.8 months
Colak et al.	2020	United States[1]	-	Retrospective CS	4	50	18 (10 - 27)	20/30	<3 weeks postexpansion
Elkenawy et al.	2020	United States[1]	-	Retrospective CS	4	31	20.4 ± 3.2	-	3 weeks
Jesus et al.[a]	2021	Brazil[13]	2017-2019	Retrospective CS	4	12	(15 - 39)	-	2 months postexpansion
Jesus et al.[b]	2021	Brazil[13]	-	Retrospective CS	4	25	23 ± 7.0	8/17	After expansion
Jia et al.	2021	China[4]	2015-2019	Prospective RCT	2	30	15.1 (12.6 - 18.1)	9/21	1 week after expansion
Kim et al.	2018	Korea[8]	2012-2017	Retrospective CS	4	14	22.7 (18.3 - 26.5)	4/10	12.0 - 15.3 months
Lee et al.	2020	Korea[9]	-	Prospective CS	4	30	20.5 (17.4 - 42.2)	12/18	At diastema appearance
Li et al.[a]	2020	China[5]	2017-2018	Retrospective CS	4	48	19.4 (15.1 - 25.6)	20/28	3 months postexpansion
Li et al.[b]	2020	China[5]	2017-2019	Retrospective CS	4	22	22.6 (18 - 35)	4/18	After 3 months retention
Lim et al.	2017	Korea[8]	2012-2017	Retrospective CS	4	24	21.6 (18.3 - 26.8)	8/16	12.0 - 16.5 months
Moon et al.	2019	Korea[10]	2011-2017	Retrospective CS	4	24	19.2 ± 5.9	14/10	3 months postexpansion
Ngan et al.	2018	United States[2]	2015-2017	Retrospective CS	4	8	21.9 ± 9.73	6/2	Immediate postexpansion

Table 1. Study characteristics of included studies. (continued)

Author	Year	Origin	Inclusion period	Study design	OCEBM Level	Sample size (n)	Mean age, years (range or ± SD)	Sex, M/F	Follow-up
Nguyen et al.	2021	Korea[11]	-	Retrospective CS	4	20	22.4 (17.6 - 27.1)	12/8	<4 weeks postexpansion
Oliveira et al.[a]	2021	Brazil[13]		Retrospective CS	4	28	(15 - 37)	10/18	After expansion
Oliveira et al.[b]	2021	Brazil[13]	2016-2019	Retrospective CS	4	17	22.9 (15 - 37)	4/13	After expansion
Paredes et al.	2020	United States[1]	-	Retrospective CS	4	39	18.2 (13.3 - 27.3)	13/26	<3 weeks postexpansion
Park et al.	2017	Korea[8]	2012-2013	Retrospective CS	4	14	20.1 (16 - 26)	9/5	24 - 66 days
Salmoria et al.	2021	Brazil[14]	-	Prospective CS	4	20	24.5 ± 1.8	10/10	After expansion
Song et al.	2019	Korea[12]	-	Retrospective CS	4	15	18.8 (9.2 - 24.5)	5/10	13 - 73 days
Storto et al.	2019	Brazil[15]	-	Retrospective CS	4	20	17,1	13/7	5 months
Tang et al.[a]	2021	China[5]	2017-2018	Retrospective CS	4	31	22.1 (18 - 33)	12/19	After debonding
Tang et al.[b]	2021	China[5]	2019-2020	Retrospective CS	4	30	23.8 (18 - 33)	9/21	3 months postexpansion
Zong et al.	2019	China[3]	2016-2018	Retrospective CS	4	22	15.0 ± 6.2	11/11	Immediate postexpansion

Abbreviations: CS, case series; OCEBM, Oxford Centre for Evidence-Based Medicine; RCT, randomized controlled trial; SD, standard deviation. Affiliations: 1 = School of Dentistry, University of California; 2 = West Virginia University School of Dentistry; 3 = School & Hospital of Stomatology, Wuhan University; 4 = Beijing Stomatological Hospital, Capital Medical University; 5 = Shandong University Dental Hospital; 6 = Faculty of Dental Medicine, George Emil Palade University of Medicine, Pharmacy, Science and Technology of Târgu Mureş; 7 = Advanced Dentistry Institute, Asunción (Paraguay); Bauru Dental School, University of São Paulo (Brazil) and Freitas Dentistry Institute, Bauru (Brazil); 8 = Yonsei University Dental Hospital; 9 = Dankook University College of Dentistry; 10 = Kyung Hee University Dental Hospital; 11 = Samsung Medical Center, Sungkyunkwan University School of Medicine; 12 = School of Dentistry, Wonkwang University Dental Hospital; 13 = School of Dentistry, São Paulo State University; 14 = Department of Orthodontics, Herminio Ometto University Center; 15 = Department of Postgraduate Orthodontics, São Leopoldo Mandic Institute and Research Center.

Table 2. Details of the MARME expansion process.

Author	Year	MARME appliance	Number of miniscrews	Miniscrews diameter/length (mm)	Bonding	Latency period (days)	Distraction rate (mm/day)	Mean activation period, days (range or ± SD)	Device activation, mm (range or ± SD)	Retention period (months)
Abedini et al.	2018	MSE	4	-	-	-	0.5^{a}	-	-	-
Almaqrami et al.	2021	Custom	4	2/8, 10 or 14	FPM, SPM, FM	-	0.5^{a}	27 (18 - 35)	6.5 (4.4 - 8.6)	3
Bud et al.^{a}	2021	MSE	4	1.8/11	FM	-	0.53-0.8^{b}			2
Bud et al.^{b}	2021	MSE	4	1.8/11	FM	-	0.53-0.8^{b}			2
Calil et al.	2021	PecLab	4	1.8/8.0	FM	-	2/4 turns^{c}	-	-	4
Cantarella et al.	2017	MSE	4	1.5/PS	FM	-	0.5^{a}	(12 - 36)	6.8 (4.1 - 10.5)	3
Cantarella et al.^{a}	2018	MSE	4	1.5/PS	FM	-	0.5^{a}	(12 - 36)	6.8 (4.1 - 10.5)	3
Cantarella et al.^{b}	2018	MSE	4	1.5/PS	FM	-	0.5^{a}	(12 - 36)	6.8 (4.1 - 10.5)	3
Choi et al.	2016	Modified hyrax	4	1.8/7.0	FPM, FM	-	0.1^{c}	-	-	3
Colak et al.	2020	MSE	4	-/11.0	FM	-	0.5-0.8^{e}	-	-	6
Elkenawy et al.	2020	MSE	4	1.5/11.0	FM	-	0.4^{f}	35 ± 10	-	6
Jesus et al.^{a}	2021	PecLab	4	-	FM	-	0.5^{g}	(14 - 18)	-	4
Jesus et al.^{b}	2021	PecLab	4	-	FM	-	0.5^{g}	(14 - 18)	-	4
Jia et al.	2021	Custom	4	1.7/12.0	FM	-	0.5^{c}	-	(5.0 - 9.1)	3
Kim et al.	2018	Modified hyrax	4	1.8/7.0	FPM, FM	1	0.2^{h}	28 (18 - 35)	6.8 (4.8 - 8.8)	3,5
Lee et al.	2020	MSE	4	1.5/11.0	FPM, FM	-	1 turn^{i}	-	7	-
Li et al.^{a}	2020	MSE	4	1.5/11.0	FM	-	0.13^{j}	-	6.1	3
Li et al.^{b}	2020	MSE	4	1.5/11.0	FM	-	0.13^{k}	38 (30 - 43)		>3
Lim et al.	2017	Modified hyrax	4	1.8/7.0	FPM, FM	-	0.2^{h}	35	6.5	4
Moon et al.	2019	MSE	4	1.5/11.0	FM	-	0.2^{h}	-		-
Nguyen et al.	2021	MSE	4	1.8/11	FM	-	0.26^{l}	48.5 (31 - 80)	6.5 (5.2 - 8.0)	3

Table 2. Details of the MARME expansion process. (continued)

Author	Year	MARME appliance	Number of miniscrews	Miniscrews diameter/length (mm)	Bonding	Latency period (days)	Distraction rate (mm/day)	Mean activation period, days (range or ± SD)	Device activation, mm (range or ± SD)	Retention period (months)
Ngan et al.	2018	MSE	2 or 4	1.8/11.0	PS	-	PS	7.6 ± 5.7 weeks	5.6 ± 1.2	-
Oliveira et al.[a]	2021	PecLab	4	1.8/9.0 or 11.0	FM	-	0.5[g]	(14 - 18)		4
Oliveira et al.[b]	2021	PecLab	4		FM	-	0.5[g]	(14 - 18)	-	-
Paredes et al.	2020	MSE	4	1.8/11.0 or 13.0	FM	-	0.2-0.4[f]	(15 - 36)	8.7 ± 1.2	6
Park et al.	2017	Modified hyrax	4	1.8/7.0	FPM, FM	-	0.2[h]	27 (18 – 35)	-	-
Salmoria et al.	2021	PecLab	4	-	FM	-	2/4 turn[m]	-	7.4	6
Song et al.	2019	MSE	4	1.5/11.0	FM	-	PS	35 (13 - 73)	-	-
Storto et al.	2019	MSE	4	1.8/11.0	FM	-	0.5[n]	-	-	-
Tang et al.[a]	2021	MSE	4	1.5/11.0	FM	-	0.13[o]	-	-	3
Tang et al.[b]	2021	MSE	4	1.5/11.0	FM	-	0.13[o]	(40 - 60)	-	3
Zong et al.	2019	MSE	4	1.8/11.0	FM	14	PS	-	-	-

Abbreviations: FM, first molar; FPM, first premolar; MSE, maxillary skeletal expander; PS, patient specific; SD, standard deviation; SPM, second premolar. Distraction rate per expansion protocol:
a, 2 turns/day (0.25mm/turn) until diastema appearance, after which one turn per day until desired expansion was attained;
b, 4–6 turns/day (0.53-0.8 mm) until diastema appearance, then 2 turns/day (0.27 mm) until crossbite overcorrection was achieved;
c, 2/4-turns/day until the palatal cusps of the maxillary first molars touch the buccal cusps of the mandibular first molars;
d, 0.2mm every other day until the maxillary cusp of either maxillary first molar touched the buccal cusp of the mandibular first molars;
e, 0.5–0.8 mm/day until diastema appearance, then 0.25 mm/day until maxillary width was equal or greater than mandibular width;
f, 2 turns/day (0.2 mm/turn) until diastema appearance, then 1 turn/day;
g, two quarter turns (0.5 mm) immediately after placement, then two quarter turns/day until full correction was achieved;
h, 1 turn/day (0.2 mm/turn) until the required expansion was achieved;
i, 1 turn/day until 7mm expansion was achieved;
j, one-sixth of a turn/day (0.13 mm) until the maxillary skeletal width was no longer less than the mandible width;
k, immediate expander activation (four turns, 0.13mm/turn), then 2 turns every other day until maxillary skeletal width was no longer less than that of the mandible;
l, 2 turns/day (0.13 mm per turn) until diastema appeared, then 1 turn/day;
m, 1/4 turn every 12 hours until diastema appearance, then 1/4 turn/day;
n, 2 turns/day (0.25 mm/turn) until necessary expansion was achieved;
o, 1 turn/day (0.13mm/turn), with a total of 40 to 60 turns.

tion of a surgical procedure and finite element studies. Next, the full text of 142 articles was reviewed. Of these, 110 were excluded with different reasons, including conference abstracts, other techniques than MARME, not meeting the age restriction, preliminary results and articles without clinical outcomes. Finally, 32 articles were included in the systematic review (**Fig. 2**). One prospective RCT was included [19], which was graded as level-2 evidence of the OCEBM criteria. All other articles were case series and classified as level-4 evidence. Next to the prospective RCT, two other prospective studies were included [20,21]. All other articles were retrospective studies (*Table 1*).

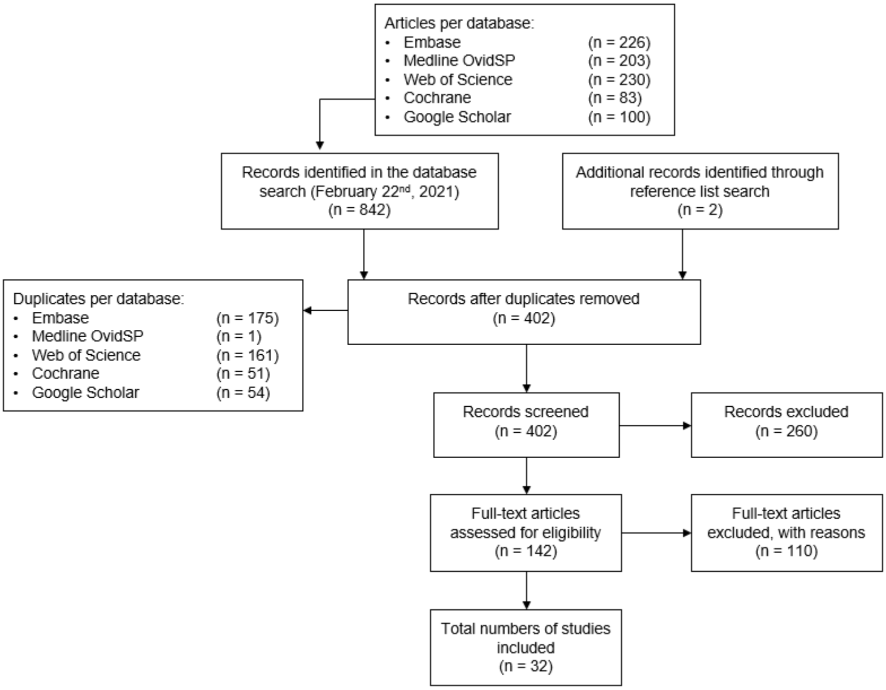

Fig. 2. Flowchart of the study selection process, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

Patient characteristics

Overlapping populations

Seven studies from UCLA School of Dentistry, Los Angeles, United States were included[22-28]. Three studies by Cantarella et al. covered the exact same population[23-25]. Further potential overlap in populations was checked with the concerning corresponding authors and revealed the following: an unclear number of patients in the studies by Abedini et al. and Elkenawy et al. overlapped to the samples from Cantarella et al.[22,27];

there was partial overlap in studies from Yonsei University Dental Hospital that included patients from 2012[29-31]: nine patients overlapped between the studies by Park et al. and Lim et al.; eleven patients overlapped between Lim et al. and Kim et al. and two patients who were not in the study by Lim et al. overlapped between Park et al. and Kim et al. Most patients in the studies by Jesus et al. were included in both studies[32,33]. Potential overlap was noticed in the two studies by Oliveira et al.[34,35]. In the studies by Jesus et al. and the studies by Oliveira et al., which were from the same institute, there was no overlap in MARME patients[32-35].

Other potential overlap was noticed for the two studies by Bud et al.[36,37]. Studies with potentially overlapping populations were included if they investigated different outcomes.

Thus, at least 490 individual patients were included in this review. Minimum mean age was limited to 14 years; the age of included patients ranged from 9.2 to 42.2 years. Most studies presented a mean age around 20 years. See *Table 1* for characteristics of the included studies.

Follow-up period

Follow-up ranged from immediately after MARME expansion to more than three years after expansion[38].

Appliance and expansion

An overview on expansion details can be found in *Table 2*.

Type of appliance

Of included studies, 20 used the Maxillary Skeletal Expander (MSE, BioMaterials Korea, Seoul, Korea) as their MARME appliance[20,22-28,36,37,39-48]. This appliance was developed by Dr. Moon and colleagues and consists of a hyrax-like appliance with a central expansion jack screw, two attached arms on each side that facilitate teeth anchorage, and insertion slots for four miniscrews[16,49]. The four studies performed at Yonsei University Dentistry Hospital used a modified hyrax appliance[29-31,38]. This appliance was developed by Dr. Lee and colleagues and consists of a conventional hyrax expander, on which four stainless steel wires with helical hooks are soldered. Miniscrews can be placed in the helical hooks and the appliance can be cemented on the first premolars and first molars[50]. Six studies used the PecLab appliance (PecLab, Belo Horizonte, Minas Gerais, Brazil), which consists of a hybrid hyrax expander, supported by four orthodontic miniscrews and bands for teeth anchorage[21,32-35,51]. Jia et al. used a custom MARME appliance composed of a jackscrew (anatomic expander type: “s;” Forestadent, Pforzheim, Germany), four tubes and two bands for teeth anchorage[19]. Almaqrami et al. used a custom MARME appliance consisting of a jackscrew, four insertion slots, a casting base and a teeth retention device. The device was cemented to the first and second premolars and the first molar[52]. All other appliances were either bonded to the first molars only or to the first premolars and first molars.

Miniscrews

Ngan et al. reported using two or four miniscrews[40]; all other studies reported using four miniscrews. Diameter of the miniscrews was either 1.5mm, 1.7mm or 1.8mm; length of the miniscrews ranged from 7.0mm to 13.0mm. MSE miniscrews are generally implanted bicortically[24]; this was explicitly reported by four studies[24,26,28,40]. Li et al. compared effects between monocortical and bicortical implantation of the miniscrews. Patients were divided into three groups: one group in which all four miniscrews were placed bicortically, one group in which only the two posterior miniscrews were placed bicortically and one group in which none of the miniscrews were placed bicortically[45]. Oliveira et al.[a] assessed cortical engagement after insertion of the miniscrews[35]. Other studies did not elaborate on cortical engagement.

Expansion protocol

Expansion rate ranged from 0.13mm/day to 0.5 mm/day. Variations in expansion protocols included a different expansion rate before and after diastema appearance and an expansion protocol based on patients' chronological age. Furthermore, multiple studies incorporated overexpansion to compensate for relapse. Ngan et al. and Zong et al. incorporated 2-3mm overexpansion, whereas Nguyen et al. incorporated 20% overexpansion[40,43,48]. Other studies incorporated a clinical overcorrection in which the palatal cusps of the first molars were almost on top of the buccal cusps of mandibular molars[19,21,51]. A latency period before initiation of expansion was uncommon; however, Kim et al. started expansion one day after appliance placement[29]; Zong et al. started expansion two weeks after appliance placement[43]. Not all studies reported a consolidation period in which the MARME appliance remained in situ to allow for bone reformation; reported periods varied between three and six months.

Corticopuncture-aided expansion

In the two studies by Bud et al., patients with stage E midpalatal suture maturation following Angelieri's classification, were treated with corticopuncture therapy before MARME[36,37]. Angelieri proposed a classification for midpalatal suture morphology. The classification consists of five radiographic stages of maturation, based on CBCT images. The following stages are distinguished: stage A, the midpalatal suture is almost a straight high-density sutural line with no or little interdigitation; stage B, the midpalatal suture assumes an irregular shape and appears as a scalloped high-density line; stage

C, the midpalatal suture appears as two parallel, scalloped, high-density lines that are close to each other, separated by small low-density spaces in the maxillary and palatine bones; stage D, the fusion of the midpalatal suture has occurred in the palatine bone, with maturation progressing from posterior to anterior and stage E, fusion of the midpalatal suture has occurred in the maxilla and the actual suture is not visible in at least a portion of the maxilla[10]. Corticopuncture therapy for the stage E patients was performed under local anesthesia. Ten bone perforations (corticopunctures) were fashioned in the midpalatal suture using a round bur with a diameter of 1.8mm. The perforations were placed approximately 2mm apart. Depth of the punctures ranged from 2 to 5mm[36,37].

Outcome assessment

Dentoalveolar effects were assessed on dental casts[38], three-dimensional (3D) tooth models derived from CBCT images[21,30,31,51], on axial CBCT slices[37,40,51] and on coronal CBCT slices[19,21,24,28,30,32,34,40,42,43,45,51].

Skeletal effects were assessed on PA cephalograms[31,38], axial CBCT slices[19,21,23,25-27,34,35,37,39,40,43,45,46,48,52] and coronal CBCT slices[19,24,27,28,30,32,34,39,40,42,43,45,46,48,51]. Song et al. used CBCT to analyse x, y and z movements of landmarks[41]. Bud et al.[b] and Jesus et al.[b] used CBCT to determine opening of the midpalatal suture[33,36].

Airway effects were analysed through volumetric measurements on CBCT[29,39,42,47]. In addition, Storto et al. performed respiratory tests[42] and Tang et al.[b] used computational fluid dynamics to analyse aerodynamic characteristics of the upper airway[47].

Soft tissue effects were analysed using 3D-photogrammetry[20,22] or facial reconstructions derived from CBCT scans[32,48].

Some studies had multiple time points during follow-up: Choi et al. performed measurements before expansion (T0), immediately after expansion (T1), immediately after debonding of fixed orthodontic appliances (T2) and at posttreatment (T3), resulting in a timeframe of more than three years[38]; Lim et al. performed measurements before expansion (T0), one month after expansion (T1) and one year after expansion[30]. Tang et al.[a] had a similar timeframe and performed measurements before expansion (T0), after expansion (T1) and one year after expansion (T2). Kim et al. analysed airway effects one year after expansion; Abedini et al. did the same for soft tissue effects[22,29].

Dentoalveolar effects

An overview on dentoalveolar effects can be found in *Table 3*.

Table 3. Overview of dentoalveolar effects.

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)	Dental and alveolar inclination (°)	Periodontal effects (mm)
Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)	Dental and alveolar inclination (°)	Periodontal effects (mm)
Bud et al.[a]	2021	20	CBCT Axial (ICIW) CBCT Coronal (FMI)	2 months postexpansion	ICIW: 4.1 ± 0.4*	FMI: 2.0 ± 0.7*	
Bud et al.[b]	2021	27	CBCT Coronal	2 months postexpansion		CanI: 4.1 ± 0.4*	FMBL: -2.1 ± 0.4*
Calil et al.	2021	16	CBCT 3D Tooth images (ICW, IFMW, IFPMW, ISPMW) CBCT Axial (BABT) CBCT Coronal (CanI, FMI, FPMI, SPMI)	After expansion	ICW: 3.0 ± 2.0^{NA} IFPMW: 3.8 ± 2.1^{NA} ISPMW: 3.4 ± 2.2^{NA} IFMW: 6.4 ± 1.7^{NA}	R CanI: 0.5 ± 1.3°^{NA} L CanI: 0.7 ± 1.6°^{NA} R FPMI: 0.2 ± 1.9°^{NA} L FPMI: -0.1 ± 2.0°^{NA} R SPMI: 0.5 ± 2.2°^{NA} L SPMI: 0.8 ± 2.3°^{NA} R FMI: 4.1 ± 3.4°^{NA} L FMI: 3.7 ± 2.9°^{NA}	R BABT at Can: −0.1 ± 0.6^{NA} L BABT at Can: 0.0 ± 0.6^{NA} R BABT at FPM: −0.0 ± 0.6^{NA} L BABT at FPM: −0.0 ± 0.4^{NA} R BABT at SPM: −0.3 ± 0.4^{NA} L BABT at SPM: −0.1 ± 0.5^{NA} R BABT at MR of FM: −0.2 ± 0.3^{NA} L BABT at MR of FM: −0.3 ± 0.4^{NA} R BABT at DR of FM: −0.3 ± 0.6^{NA} L BABT at DR of FM: −0.6 ± 0.5^{NA}

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)			Dental and alveolar inclination (°)	Periodontal effects (mm)
Cantarella et al.[a]	2018	15	CBCT Coronal	< 3 weeks after expansion	IFMW: 8.3 ± 2.3*			R MI: 2.0 ± 1.0°* L MI: 2.5 ± 1.8°* R MBBA: 2.0 ± 3.3° L MBBA: 1.8 ± 4.3°	
Choi et al.	2016	20	Dental casts	T0: Before expansion T1: Immediately after expansion T2: Immediately after debonding T3: At posttreatment *T2-T0 = 21.6 ± 6.4 months*	T1-T0 (95% CI) ICW: 2.9 (2.1 - 3.6)* IFPMW: 6.1 (5.4 - 6.8)* IFMW: 8.3 (7.3 - 9.4)*	T2-T0 (95% CI) ICW: 2.4 (1.6 - 3.2)* IFPMW: 4.2 (3.4 - 4.9)* IFMW: 4.4 (3.4 - 5.5)*	T3-T0 (95% CI) ICW: 2.3 (1.5 - 3.1)* IFPMW: 3.8 (3.1 - 4.4)* IFMW: 4.0 (3.0 - 5.1)*		
				Relapse: *T2-T1 = 17.4 ± 6.4 months* *T3-T2 = 30.2 ± 13.2 months*	T2-T1 (95% CI) ICW: -0.5 (-0.7/-0.3)* IFPMW: -1.9 (-2.6/-1.3)* IFMW: -3.9 (-4.9/-2.8)*	T3-T2 (95% CI) ICW: -0.1 (-0.3 - 0.1) IFPMW: -0.4 (-0.7/-0.1) IFMW: -0.4 (-0.7/-0.2)*			
Jesus et al.[a]	2021	12	CBCT Coronal	1-2 months after expansion	IFMW: 5.8 ± 2.0*				

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)	Dental and alveolar inclination (°)	Periodontal effects (mm)
Jia et al.	2021	30	CBCT Coronal	1 week after expansion	IFPMW-CF: 5.0 ± 1.2* IFPMW-apex: 4.8 ± 1.5* IFMW-CF: 6.4 ± 1.3* IFMW-apex: 3.7 ± 1.1*	R FPMI: 0.6 ± 2.9° L FPMI: 0.6 ± 3.2° R FMI: 3.8 ± 4.1°* L FMI: 2.7 ± 3.4°*	R BACH at FPM: -0.5 ± 0.9* L BACH at FPM: -0.4 ± 0.9* R BACH at FM: -0.4 ± 1.0* L BACH at FM: -0.8 ± 1.0*
Li et al.[a]	2020	48	CBCT Coronal	3 months after expansion	Four bicortical miniscrews IFMW-CF: 6.8 ± 1.3* IFMW-apex: 5.4 ± 0.9* Two bicortical miniscrews IFMW-CF: 6.9 ± 1.1* IFMW-apex: 5.3 ± 1.0* No bicortical miniscrews IFMW-CF: 7.2 ± 1.4* IFMW-apex: 3.6 ± 1.3*	Four bicortical miniscrews R FMI: 0.6 ± 0.6°* L FMI: 0.4 ± 0.5°* R AI: 0.8 ± 0.9°* L AI: 0.6 ± 0.5°* Two bicortical miniscrews R FMI: 1.1 ± 0.6°* L FMI: 1.0 ± 0.8°* R AI: 1.4 ± 1.2°* L AI: 1.3 ± 1.1°* No bicortical miniscrews R FMI: 2.0 ± 1.3°* L FMI: 2.1 ± 1.2°* R AI: 4.9 ± 3.3°* L AI: 4.7 ± 3.9°*	Four bicortical miniscrews R BACH: –0.7 ± 0.5* L BACH: –0.5 ± 0.5* Two bicortical miniscrews R BACH: –0.6 ± 0.3* L BACH: –0.7 ± 0.6* No bicortical miniscrews R BACH: –0.8 ± 0.4* L BACH: –0.4 ± 0.9*

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)		Dental and alveolar inclination (°)		Periodontal effects (mm)	
Lim et al.	2017	24	Inter-cusp width: CBCT 3D Tooth Images (Inter-cusp width) CBCT Coronal (Inter-apex width, FMI, BABT, PABT, BACH)	T0: Before expansion T1: < 1 month after expansion *(mean: 9.5 days, range 0–28)* T2: One year after expansion *(mean: 14.2 months; range 12.0–16.5)*	T1-T0 *Inter-cusp width / Inter-apex width* ICIW: −1.1 ± 1.1* / 3.1 ± 1.0* ICW: 3.0 ± 1.3* / 2.4 ± 1.2* IFPMW: 6.0 ± 1.2* / 3.6 ± 1.6* ISPMW: 5.8 ± 1.3* / 1.6 ± 1.4* IFMW: 5.6 ± 1.9* / 2.8 ± 1.4*	T2-T0 *Inter-cusp width / Inter-apex width* ICIW: −0.4 ± 0.6* / 0.5 ± 1.4 ICW: 3.0 ± 2.4* / 3.4 ± 2.0* IFPMW: 5.0 ± 2.2* / 2.4 ± 1.8* ISPMW: 3.9 ± 2.2* / 1.8 ± 1.4* IFMW: 3.6 ± 3.2* / 2.7 ± 2.0*	T1-T0 FMI: 3.9 ± 2.5°* AI: 1.8 ± 2.4°*	T2-T0 FMI: 1.6 ± 4.6° AI: 2.3 ± 4.9°*	T1-T0 BABT at FPM: −0.5 ± 0.4* BABT at SPM: −0.1 ± 0.4 BABT at FM: −0.4 ± 0.3* PABT at FPM: 0.9 ± 0.8* PABT at SPM: 0.4 ± 0.5* PABT at FM: 0.6 ± 0.6* BACH at FPM: -2.3 ± 3.0* BACH at SPM: -0.7 ± 0.6* BACH at FM: -0.7 ± 0.9*	T2-T0 BABT at FPM: −0.3 ± 0.4* BABT at SPM: −0.4 ± 0.6* BABT at FM: −0.1 ± 0.6 PABT at FPM: 0.5 ± 0.8* PABT at SPM: 0.2 ± 0.6 PABT at FM: 0.3 ± 0.4* BACH at FPM: -1.5 ± 2.0* BACH at SPM: -0.2 ± 1.1 BACH at FM: -0.3 ± 0.7

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)	Dental and alveolar inclination (°)	Periodontal effects (mm)
				Relapse	T2-T1 *Inter-cusp width / Inter-apex width* ICIW: −1.6 ± 1.3* / −2.6 ± 1.7* ICW: −0.7 ± 2.4 / 1.0 ± 1.9* IFPMW: −1.0 ± 2.6 / −1.2 ± 1.4* ISPMW: −1.9 ± 2.5* / 0.2 ± 1.5 IFMW: −2.0 ± 2.9* / 0.1 ± 1.3	T2-T1 FMI: -2.3 ± 4.6°* AI: 0.5 ± 4.9°	T2-T1 BABT at FPM: 0.3 ± 0.6* BABT at SPM: −0.3 ± 0.6 BABT at FM: 0.2 ± 0.6* PABT at FPM: −0.5 ± 0.7* PABT at SPM: −0.2 ± 0.6* PABT at FM: −0.3 ± 0.5* BACH at FPM: −0.9 ± 2.4 BACH at SPM: −0.5 ± 1.0* BACH at FM: −0.4 ± 1.0
Moon et al.	2019	24	CBCT Coronal	3 months after expansion	IFMW: 4.9 ± 1.5*	R FMI: 2.8 ± 2.0°* L FMI: 2.0 ± 2.2°* R AI: 0.7 ± 1.2°* L AI: 0.9 ± 1.3°*	R BABT at FM: -0.7 ± 0.4* L BABT at FM: -0.5 ± 0.5* R BACH at FM: -1.2 ± 1.8* L BACH at FM: -1.5 ± 1.8*

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)	Dental and alveolar inclination (°)	Periodontal effects (mm)
Ngan et al.	2018	8	CBCT Axial (BABT) CBCT Coronal (FPMI, FMI, AI)	Immediately after expansion	IFMW: 6.3 ± 1.3^{NA}	R FPMI: 2.6 ± 5.4° L FPMI: 9.2 ± 6.0°* R FMI: 8.0 ± 4.8°* L FMI: 5.6 ± 2.8°* R AI at FPM: 8.3 ± 13.2° L AI at FPM: -2.3 ± 10.7° R AI at FM: 3.1 ± 4.9° L AI at FM: 1.5 ± 5.6°	R BABT at FPM: −0.5 ± 0.5* L BABT at FPM: -0.7 ± 0.7* R BABT at MR of FM: −0.6 ± 0.5* L BABT at MR of FM: −0.4 ± 0.5 R BABT at DR of FM: −0.5 ± 0.3* L BABT at DR of FM: −0.3 ± 0.3*
Oliveira et al.[b]	2021	17	CBCT Coronal	After expansion	*Inter-cusp width / Inter-apex width* IFPMW: 5.2 ± 2.3* / 4.0 ± 1.8* IFMW: 5.3 ± 2.3* / 3.8 / 1.6*	R FPMI: 1.4 ± 1.7* L FPMI 1.9 ± 2.3* R FMI: 2.9 ± 1.9* L FMI: 3.4 ± 2.4*	
Paredes et al.	2020	39	CBCT Coronal	<3 weeks postexpansion	R FM to midline: 3.8 ± 1.7* L RM to midline: 4.2 ± 1.9*	R FMI: 2.9 ± 1.3°* L FMI: 3.1 ± 1.5°* R AI: 2.8 ± 1.3°* L AI: 2.9 ± 1.5°*	

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)		Dental and alveolar inclination (°)		Periodontal effects (mm)
Park et al.	2017	14	CBCT 3D Tooth Images (IFPMW, IFMW) CBCT Coronal (BABT, BACH, IDA)	< 5 weeks after expansion	IFPMW: 5.5 ± 1.4* IFMW: 5.4 ± 1.7*		IDA FPM: 2.2 ± 10.6° IDA FM: 5.8 ± 5.7°*		BABT at FPM: -1.1 ± 0.8* BABT at FM: -0.6 ± 1.0* BACH at FPM: -2.2 ± 3.5* BACH at FM: -1.7 ± 2.5*
Salmoria et al.	2021	20	CBCT 3D Tooth Images (IFPMW, IFMW) CBCT Coronal (FMI, FPMI)	After expansion	Group D (min - max) IFPMW: 4.6 (2.6 - 7.4)^{NA} IFMW: 6.6 (4.0 - 8.5)^{NA}	Group E (min - max) IFPMW: 4.6 (3.4 - 6.2)^{NA} IFMW: 7.1 (5.4 - 9.8)^{NA}	Group D (min - max) R FPMI: 2.3 (1.5 - 3.8)^{NA} L FPMI: 3.1 (1.6 - 6.8)^{NA} R FMI: 3.1 (2.1 - 6.1)^{NA} L FMI: 3.7 (1.3 - 5.8)^{NA}	Group E (min - max) R FPMI: 7.4 (3.9 - 9.9)^{NA} L FPMI: 6.3 (3.4 - 8.5)^{NA} R FMI: 7.1 (3.0 - 9.4)^{NA} L FMI: 6.1 (2.0 - 9.0)^{NA}	

Table 3. Overview of dentoalveolar effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Dental expansion (mm)	Dental and alveolar inclination (°)	Periodontal effects (mm)
Storto et al.	2019	20	CBCT Coronal	After expansion	IFPMW: 3.6* IFMW: 5.3*	FPMI: 1.8° FMI: 3.6°*	
Zong et al.	2019	22	CBCT Coronal	Immediately after expansion	IFMW: 5.4 ± 2.2*	R FMI: 2.3°* L FMI: 2.6°*	

Abbreviations: *, significant $p < 0.05$; 3D, three-dimensional; AI, alveolar inclination; BABT, buccal alveolar bone thickness; BACH, buccal alveolar crest height; Can, canine; CanI, canine inclination; CBCT, cone-beam computed tomography; CF, central fossa; CI, confidence interval; DR, distal root; FM, first molar; FMBL, first molar bone level; FMI, first molar inclination; FPM, first premolar; FPMI, first premolar inclination; ICIW, inter central incisor width; ICW, intercanine width; IDA, interdental angle; IFMW, inter first molar width; IFPMW, inter first premolar width; ISMW, inter second molar width; ISPMW, inter second premolar width; L, left; max, maximum; MI, maxillary inclination; min, minimum; MBBA, molar basal bone angle; MR, mesial root; NA, not statistically analysed; PABT, palatal alveolar bone thickness; R, right; SPM, second premolar; SPMI, second premolar inclination.

Expansion

Assessment of dental effects included measurements on the inter canine width (ICW), measured between the cusp tips[30,38,51] and root apices[30]; inter first premolar width (IFPMW), measured between the mesial fossae[38], central fossae[19,42], buccal cusps[21,30,31,34,51], buccal root apices[30] and palatal root apices[19,34]; inter second premolar width (ISPMW), measured between the buccal cusps[30,51]; inter first molar width (IFMW), measured between the central fossae[19,32,38,42,44,45], mesiobuccal cusps[21,24,30,31,34,51], mesiopalatal cusps[40,43], buccal root apices[30] and palatal root apices[19,34,45]. Next to this, Lim et al. and Bud et al.[a] measured the inter central incisors width(ICIW)[30,37]; Paredes et al. measured right and left distance of the central groove of the first molar to the midline[28]. Salmoria et al. measured IFPMW and IFMW separately for patients with stage D (mean age 18.8 ± 0.6 years) and stage E (mean age 31.0 ± 5.2 years) midpalatal suture maturation. Measurements were performed before treatment initiation and after conclusion of expansion[21].

A statistically significant increase in ICW, IFPMW, IFMW, and ISMW was observed. ICW change ranged from 2.3mm (95% CI: 1.5 - 3.1) to 3.4 ± 2.0; IFPMW ranged from 3.1 ± 2.3mm to 6.1mm (95% CI: 5.4 - 6.8); ISPMW ranged from 3.6 ± 2.0mm to 5.8 ± 1.3mm; IFMW ranged from 3.9 ± 2.4mm to 8.3 ± 2.3mm; ISMW change was 3.6 ± 2.5mm. Choi et al., who had the longest follow-up, reported the following changes at their final assessment: ICW, 2.3mm (95% CI: 1.5 – 3.1); IFPM, 3.8mm (3.1 - 4.4); IFMW, 4.0mm (3.0 - 5.1). Despite significant relapse for all parameters, significant width increases ($p < 0.001$) were still observed at the final assessment[38]. Changes in inter-apex width of the IFPMW, ISPMW and IFMW were generally lower than changes in inter-buccal cusp or inter-central fossae width[30,45].

Dental inclination

Inclination of first molars was assessed in thirteen studies[19,21,24,28,30,34,37,40,42-45,51]. Ngan et al. reported a significant increase in inclination of 8.0 ± 4.8° ($p = 0.005$) for the right first molar[40]. After significant relapse, Lim et al. observed a nonsignificant increase in inclination of 1.6 ± 4.6° ($p > 0.05$) of the first molar at one year after expansion[30]. Li et al. found that monocortical screws (right first molar: 2.0 ± 1.3) led to significantly more tipping compared to bicortical screws (right first molar: 0.6 ± 0.6, $p = 0.00$)[45]. Inclination of the first premolars was assessed in six studies[19,21,34,40,42,51]. Compared to first molars, first premolars showed lower increases in inclination. Other measurements included inclination of the canine[37,51] and second premolars[51]; the molar basal bone angle, formed between a horizontal line from the most lateral maxillary point to the nasal cavity floor and a vertical line through the tooth axis[24]; and the interdental angle, which consisted of the angle between a line through the right and left axes of the concerning tooth[31].

Alveolar inclination

Five studies reported on changes in alveolar inclination[28,30,40,44,45]. Similar to first molar inclination, Li et al. found significantly more alveolar inclination for monocortical screws (right alveolar inclination: 4.9 ± 3.3°) compared to bicortical screws (right alveolar inclination: 0.8 ± 0.9°, $p = 0.00$). One year after expansion, Lim et al. found a significant increase in alveolar inclination of 2.3 ± 4.9° ($p < 0.05$)[30,45]. Ngan et al. found more varying results, ranging from -2.3 ± 10.7° at the left first premolar to 8.3 ± 13.2° at the right first premolar[40]. Moon et al. found significant first molar inclination of 0.7 ± 1.2° ($p = 0.006$) on the right side and 0.9 ± 1.3° ($p = 0.003$) on the left side[44].

Periodontal effects

Main parameters for analyses of periodontal effects were changes in alveolar bone thickness and alveolar crest height[19,30,31,36,40,45,51]. Lim et al. analysed alveolar bone thickness on the buccal and palatal sides of the first and second premolars and the first molars. One year post-expansion, buccal alveolar bone thickness was significantly decreased for the first and second premolars (-0.3 ± 0.4mm ($p < 0.01$) and -0.4 ± 0.6mm ($p < 0.01$) respectively); palatal alveolar bone thickness increased significantly for the first premolar and first molar (0.5 ± 0.8mm ($p < 0.01$) and 0.3 ± 0.4mm ($p < 0.01$) respectively)[30]. Ngan et al. measured buccal alveolar bone thickness for the first premolars and for the mesial and distal buccal roots of the first molars. Except for the mesial buccal root of the left first molar, the buccal alveolar bone thickness decreased significantly for all other measurement sites, ranging from -0.3 ± 0.3mm ($p = 0.02$) for the distal buccal root of the left first molar to -0.7 ± 0.7mm ($p = 0.04$) for the left first molar[40]. Consistently with these findings, significant decreases in buccal alveolar bone thickness were observed by Park et al. ($p < 0.005$) and Moon et al. ($p < 0.004$) as well[31,44]. Calil et al. measured buccal alveolar bone thickness for the canine and first and second premolars as well as the mesial and distal root of the first molars. Statistical significance was not reported for pre- and post MARME changes[51].

Buccal alveolar crest height loss was analysed by six studies[19,30,31,36,44,45]. In general, a loss of buccal alveolar crest height was seen. After one year, Lim et al. found a significant loss of 1.5 ± 2.0mm ($p < 0.01$) at the first premolar; alveolar height reduction was nonsignificant at the second premolar and first molar[30]. Li et al. found no significant difference in buccal alveolar crest height loss between monocortical or bicortical screws[45]. Bud et al.[b] measured alveolar crest height loss at the buccal and palatal sides and found alveolar crest height loss in 11 patients, with a mean loss of 2.1 ± 0.4mm[36].

Skeletal effects

An overview of skeletal effects after MARME can be found in *Table 4*.

Table 4. Overview of skeletal effects.

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)
Almaqrami et al.	2021	49	CBCT Axial	< 3 weeks after expansion		IMLFW: 4.3 ± 1.0* IPMWW: 4.3 ± 1.1* IGPFW: 3.8 ± 0.9*
Bud et al.[a]	2021	20	CBCT Axial	2 months postexpansion		MPSE at ANS: 3.8 ± 0.5^{NA} MPSE at PNS: 3.1 ± 0.4^{NA}
Bud et al.[b]	2021	27	CBCT	2 months postexpansion	88,9	
Calil et al.	2021	16	CBCT Coronal	After expansion		NCW: 2.8 ± 1.5^{NA} MxW: 3.1 ± 1.8^{NA}
Cantarella et al.	2017	15	CBCT Axial	< 3 weeks after expansion	100%	RD of ANS: 2.6 ± 1.7* LD of ANS: 2.2 ± 1.3* TD of ANS: 4.8 ± 2.6* RD of PNS: 2.3 ± 1.3* LD of PNS: 2.0 ± 0.9* TD of PNS: 4.3 ± 1.7* Right PSO: 1.4 ± 1.8* Left PSO: 2.2 ± 2.5*
Cantarella et al.[a]	2018	15	CBCT Coronal	< 3 weeks after expansion	100%	UIZD: 0.5 ± 0.4* LIZD:4.6 ± 1.3* R FZA: 2.5 ± 1.3°* L FZA: 2.9 ± 1.4°* R ZMA: -0.2 ± 0.9° L ZMA: -0.4 ± 1.0°

Table 4. Overview of skeletal effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)		
Cantarella et al.[b]	2018	15	CBCT Axial	< 3 weeks after expansion	100%	AIZW: 2.8 ± 1.5* PIZW: 2.4 ± 0.6* PITW: 0.0 ± 0.1 Right ZTA: -0.1 ± 1.1° Left ZTA: -0.0 ± 1.5° Right ZPA: 1.7 ± 1.1°* Left ZPA: 2.1 ± 1.6°*		
Choi et al.	2016	20	PA cephalograms	T0: Before expansion T1: Immediately after expansion T2: Immediately after debonding T3: At posttreatment *T2-T0 = 21.6 ± 6.4 months*	86,9%	T1-T0 (95% CI) NCW: 1.1 (0.6 - 1.5)* MxW: 2.1 (1.5 - 2.7)* AW: 2.2 (1.6 - 2.9)*	T2-T0 (95% CI) NCW: 0.9 (0.4 - 1.3)* MxW: 1.9 (1.3 - 2.5)* AW: 2.0 (1.4 - 2.6)*	T3-T0 (95% CI) NCW: 0.8 (0.3 - 1.3)* MxW: 1.9 (1.3 - 2.5)* AW: 2.0 (1.3 - 2.6)*
				Relapse: *T2-T1 = 17.4 ± 6.4 months* *T3-T2 = 30.2 ± 13.2 months*		T2-T1 (95% CI) NCW: -0.2 (-0.4/-0.1) MxW: -0.2 (-0.4/0.0) AW: -0.2 (-0.4/-0.1)	T3-T2 (95% CI) NCW: -0.1 (-0.2/0.1) MxW: -0.1 (-0.2/0.0) AW: -0.1 (-0.2/0.1)	
Colak et al.	2020	50	CBCT Axial	< 3 weeks after expansion		MPSOA: 0.6° (-0.8° - 1.3°)*		
Elkenawy et al.	2020	31	CBCT Axial (ANS, PNS) CBCT Coronal (ZMC)	3 weeks after expansion		TD of ANS: 5.0 ± 1.9* TD of PNS: 4.8 ± 2.7* TD of ZMC: 4.0 ± 1.6*		

Table 4. Overview of skeletal effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)
Jesus et al.[a]	2021	12	CBCT Coronal	1-2 months after expansion		NCW at Can: 2.3 ± 2.0* NCW at FM: 2.8 ± 1.9* NFW at Can: 3.0 ± 1.3* NFW at FM: 3.5 ± 2.0* MxW at FM: 3.2 ± 1.9*
Jesus et al.[b]	2021	25	CBCT	After expansion	76%	
Jia et al.	2021	30	CBCT Axial (ANS, FPM, FM, PNS) CBCT Coronal (NCW, MxW, AW)	1 week after expansion	100%	NCW at FPM: 3.4 ± 0.9* NCW at FM: 2.8 ± 0.8* MxW at FPM: 4.5 ± 1.2* MxW at FM: 3.9 ± 1.2* AW at FPM: 4.8 ± 1.2* AW at FM: 4.0 ± 1.0 MPSE at ANS: 4.4 ± 1.0* MPSE at FPM: 4.2 ± 1.0* MPSE at FM: 3.8 ± 0.8* MPSE at PNS: 3.1 ± 0.6*
Lee et al.	2020	30	NR	At diastema appearance	93,5%	

Table 4. Overview of skeletal effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)		
Li et al.[a]	2020	48	CBCT Axial (ILPW, ITW, IZW) CBCT Coronal (NCW, MxW, AW)	3 months after expansion		Four bicortical miniscrews NCW at FM: 3.3 ± 1.1* MxW at FM: 4.2 ± 1.2* AW at FM: 4.6 ± 1.2* ILPW: 1.7 ± 1.6* ITW: 0.6 ± 0.4* IZW: 2.1 ± 0.8*	Two bicortical miniscrews NCW at FM: 3.0 ± 1.2* MxW at FM: 4.0 ± 1.1* AW at FM: 4.3 ± 1.0* ILPW: 1.3 ± 0.3* ITW: 0.5 ± 0.4* IZW: 2.0 ± 0.7*	No bicortical miniscrews NCW at FM: 2.1 ± 1.0* MxW at FM: 2.3 ± 1.1* AW at FM: 3.2 ± 1.1* ILPW: 0.3 ± 0.3* ITW: 0.2 ± 0.3 IZW: 1.1 ± 0.9*
Li et al.[b]	2020	22	CBCT Axial (AIZD, AITD) CBCT Coronal (NCW, NFW, MxW, AW)	< 3 months after expansion		NCW: 2.3 ± 1.2* NFW: 2.3 ± 1.2* MxW at NF: 1.7 ± 1.1* AW: 2.0 ± 1.0* AIZW: 0.5 ± 1.0* AITW: 0.7 ± 0.5*		
Lim et al.	2017	24	CBCT Coronal	T0: Before expansion T1: < 1 month after expansion T2: One year after expansion	86,8%	T1-T0 NCW at FM: 1.6 ± 0.9* NFW at FM: 2.2 ± 1.0* AW at FM: 2.6 ± 0.9*	T2-T0 NCW at FM: 1.3 ± 0.8* NFW at FM: 1.6 ± 1.0* AW at FM: 2.1 ± 1.1*	

Table 4. Overview of skeletal effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)
				Relapse		T2-T1 NCW at FM: -0.4 ± 0.4* NFW at FM: -0.6 ± 0.7* AW at FM: -0.5 ± 0.9*
Moon et al.	2019	24	CBCT Coronal	3 months after expansion		NFW at FM: 2.5 ± 1.4*
Ngan et al.	2018	8	CBCT Axial (Can, FPM, SPM, FM) CBCT Coronal (SEM, FMW, NF, PF, AI)	Immediately after expansion	100%	SEM: 2.6 ± 0.7^{NA} FMW: 3.3 ± 0.8^{NA} MPSE at Can: 3.5 ± 0.8^{NA} MPSE at FPM: 3.7 ± 0.6^{NA} MPSE at SPM: 3.6 ± 0.7^{NA} MPSE at FM: 3.3 ± 0.5^{NA} MPSE at NF: 2.5 ± 0.5^{NA} MPSE at PF: 2.9 ± 0.6^{NA}
Nguyen et al.	2021	20	CBCT Axial (ANS, PNS) CBCT Coronal (AW)			ANS: 4.8 ± 0.5* PNS: 4.0 ± 0.5* AW at FM: 4.2 ± 0.7*
Oliveira et al.[a]	2021	28	CBCT Axial	After expansion	71,4%	
Oliveira et al.[b]	2021	17	CBCT Axial (IInFW, IIFW, IGPFW) CBCT Coronal (NCW, MxW, AW)	After expansion		IInFW: 2.9 ± 1.2* IIFW: 3.7 ± 1.4* IGPFW: 2.8 ± 0.9* NCW at FPM: 2.9 ± 2.0* NCW at FM: 2.9 ± 1.1* MxW at FPM: 3.3 ± 2.6* MxW at FM: 2.3 ± 1.1* AW at FPM: 4.3 ± 1.9* AW at FM: 3.9 ± 1.2*

Table 4. Overview of skeletal effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)	
Paredes et al.	2020	39	CBCT Coronal	<3 weeks postexpansion		RD of ZMC: 2.3 ± 1.0* LD of ZMC: 2.4 ± 1.2* R ABD: 2.9 ± 1.2* L ABD: 3.1 ± 1.5* R FZA: 2.8 ± 1.3°* L FZA: 2.9 ± 1.5°*	
Park et al.	2017	14	PA cephalograms	< 5 weeks after expansion	84,2%	NCW: 1.4 ± 1.0* MxW: 2.0 ± 1.4* AW: 2.4 ± 1.3* FMW: 3.2 ± 1.5 IZW: 0.8 ± 0.5*	
Salmoria et al.	2021	20	CBCT Axial	After expansion		Group D (min - max) MPSE at ANS: 5.3 (3.8 - 7.0)^{NA} MPSE at PNS: 3.9 (2.1 - 5.2)^{NA}	Group E (min - max) MPSE at ANS: 3.7 (2.8 - 5.9)^{NA} MPSE at PNS: 2.4 (2.1 - 4.0)^{NA}

Table 4. Overview of skeletal effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)		
Song et al.	2019	15	CBCT 3D landmark coordinates X: right and left of nasion Y: antero- (-) and posteronasal (+) Z: infra- (-) and supranasal (+)	After expansion		*X-coordinates* RD of ANS: 1.1 ± 0.6* LD of ANS: 1.1 ± 0.5* RD of PNS: 1.0 ± 0.3 LD of PNS: 1.0 ± 0.6 Z: 0.5 ± 0.3* J: 1.2 ± 0.6*	*Y-coordinates* ANS: −0.3 ± 0.2* PNS: −0.6 ± 0.6* Z: −0.5 ± 0.6* J: −0.0 ± 0.6 SNA: 0.5 ± 0.8°* SNB: -0.6 ± 0.6°* ANB: 1.0 ± 0.7°*	*Z-coordinates* ANS: −0.4 ± 0.4* PNS: −1.2 ± 0.4* Z: −0.1 ± 0.6 J: −0.3 ± 0.4*
Storto et al.	2019	20	CBCT Coronalniet vet	After expansion		NCW at FPM: 3.5* NCW at FM: 2.2* MPSE at FPM: 4.7* MPSE at FM: 4.0* AW at FPM: 3.6* AW at FM: 3.9*		
Tang et al.[a]	2021	31	CBCT Axial (ILPW, ITW, IZW) CBCT Coronal (NCW, MxW, AW)	T0: Before expansion T1: After retention T2: After debonding *T1-T0: 6 ± 1.9 months*	92%	<u>T1-T0</u> NCW at FM: 2.3 ± 1.1* MxW at FM: 2.3 ± 1.2* AW at FM: 2.7 ± 1.0* ILPW: 1.6 ± 0.8* ITW: 1.3 ± 1.0* IZW: 1.5 ± 1.0*	<u>T2-T0</u> NCW at FM: 2.1 ± 1.1* MxW at FM: 2.0 ± 1.3* AW at FM: 2.2 ± 1.1* ILPW: 1.3 ± 0.9* ITW: 1.1 ± 1.1* IZW: 1.2 ± 1.0*	

Table 4. Overview of skeletal effects. (continued)

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Midpalatal suture opening succes rate	Reported outcome changes (width: mm, angle: °)
				Relapse: *T2-T1: 13 ± 2.2 months*		T2-T1 NCW at FM: -0.1 ± 0.2* MxW at FM: -0.4 ± 0.3* AW at FM: -0.4 ± 0.4* ILPW: -0.3 ± 0.3* ITW: -0.2 ± 0.2* IZW: -0.3 ± 0.3*
Zong et al.	2019	22	CBCT Coronal (NF, PF) CBCT Axial (ASI, PSI)	Immediately after expansion		MPSE at NF: 2.8 ± 1.5^{NA} MPSE at PF: 3.3 ± 1.8^{NA} MPSE at ASI: 3.1 ± 1.6^{NA} MPSE at PSI: 3.3 ± 1.7^{NA}

Abbreviations: ABD, alveolar bone displacement; AIMD, anterior inter-maxillary width; AITW, anterior inter-temporal width; AIZW, anterior inter-zygomatic width; ANB, a-point nasion b-point angle; ANS, anterior nasal spine; ASI, anterior screw insertion site; AW, alveolar width; Can, canine; CI, confidence interval; FM, first molar; FMW, first molar width; FPM, first premolar; FZA, fronto-zygomatic angle; IGPFW, inter greater palatine foramen width; IInFW, inter infraorbital foramen width; IIFW, inter incisive foramen width; IMLFW, inter maxillary lateral fossa width; ILPW, inter lateral pterygoid plate width; IPMWW, inter posterolateral maxillary wall width; ITW, inter-temporal width; IZW, inter-zygomatic width; J, jugular process; L, left; LD, left displacement; LIZD, lower niet vetinter-zygomatic distance; MPSE, midpalatal suture expansion; MPSOA, midpalatal suture opening angle; MxW, maxillary width; NA, not statistically analysed; NCW, nasal cavity width; NF, nasal floor; NFW, nasal floor width; NR, not reported; PITW, posterior inter-temporal width; PIZW, posterior inter-zygomatic width; PF, palatal floor; PNS, posterior nasal spine; PSI, posterior screw insertion site; PSO, pterygopalatine suture opening; R, right; RD, right displacement; SEM, suture expansion at middle palate; SM, second molar; SNA, sella nasion subspinal angle; SNB, sella nasion supramental angle; SPM, second premolar; TD, total displacement; UIZD, upper inter-zygomatic distance; Z, most lateral point on the zygomatic arch on the coronal plane; ZMA, zygomatico-maxillary angle; ZMC, zygomatico-maxillary complex; ZPA, zygomatic process angle; ZTA, zygomaticotemporal angle.

Maxillary expansion

Cantarella et al. found a significant increase of 2.8 ± 1.5mm ($p < 0.0001$) at the most anterior points of both maxillary bones[25]. Choi et al. reported significant width increases at the level of the maxillary bone (1.9mm, 95% CI: 1.3 – 2.5mm, $p < 0.001$) and at the level of the alveolar bone (2.0mm, 95%CI: 1.3 – 2.6mm, $p < 0.001$), which were stable more than three years after expansion. Relapse in between was nonsignificant[38]. Lim et al. presented results one year after expansion; relapse of increase in alveolar bone width was significant (-0.5 ± 0.9mm, $p < 0.05$), but a significant expansion of 2.1 ± 1.1mm ($p < 0.01$) remained[30]. Other studies investigated increases in maxillary width and alveolar bone width as well. Except for Calil et al., who did not provide statistical significance for pre- and post MARME changes, all studies found significant increases of maxillary width and alveolar bone width[19,31,32,34,39,45,46,51]. Li et al.[a] found a significantly higher increase of maxillary and alveolar width with bicortical screws compared to monocortical screws[45]. Almaqrami et al. included width increases between the maxillary lateral fossae (4.3 ± 1.0mm, $p = 0.000$), the posterolateral maxillary walls (4.3 ± 1.1mm, $p = 0.000$) and the greater palatine foramina (3.8 ± 0.9mm, $p = 0.000$)[52]. Oliveira et al.[b] included width increases between the incisive foramina (3.7 ± 1.4mm, $p < 0.001$) as well as the greater palatine foramina (2.8 ± 0.9mm, $p < 0.001$)[34]. Furthermore, increase of maxillary width at the first molar level was analysed by two studies: Ngan et al. found an increase of 3.3 ± 0.8mm immediately after expansion; Park et al. observed a significant increase of 3.2 ± 1.5mm ($p = 0.000$)[31,40].

Successful midpalatal suture opening

A number of studies reported on excluding patients in whom midpalatal suture opening after MARME failed[20,21,29-31,33,36,39,41,42,44,48,51]. Oliveira et al.[a] analysed factors associated to successful midpalatal suture opening. Success rate in patients aged 15 to 19 ($n = 12$) was 83.3%. For ages 20 to 29 ($n = 11$), success rate was 81.8% and for ages 30 to 39 ($n = 5$), success rate was 20.0%, resulting in an average success rate of 71.4%. For sex and bicortical screws, no correlation was found to successful midpalatal suture opening[35]. Jesus et al.[b] analysed midpalatal suture characteristics to predict successful suture opening. In patients aged up to 25 years, the authors report a 94.1% success rate, which decreases to 76% when patients up to 37 years old were included as well. Next to age, the authors considered midpalatal bone thickness in a region 12-16mm posterior to the incisive foramen relevant factors in successful suture opening[33]. In their study randomizing consecutive patients between MARME and RME, Jia et al. observed suture opening in all MARME patients (mean age 15.1 years), compared to 86.7% of RME patients (mean age 14.8 years)[19]. Cantarella et al. and Ngan et al. observed suture opening in all of their consecutively included patients as well[23,40]. Cantarella et al. found age and sex to be negligible factors in midpalatal suture opening[23]. Next to opening of the midpalatal suture, Cantarella et al. and Colak et al. observed splitting of the pterygopalatine suture in 53% and 84% of their populations, respectively[23,26].

Midpalatal suture expansion

Midpalatal suture expansion (MPSE) was assessed at different levels. Cantarella et al. measured left and right sided lateral changes of the anterior nasal spine (ANS) and posterior nasal spine (PNS) relative to a sagittal plane running through the ANS, PNS and nasion. The authors found significant MPSE at the ANS and PNS ($p < 0.0001$)[23]. Salmoria et al., Bud et al.[a] and Nguyen et al. assessed MPSE at the ANS and PNS as well[21,37,48]. Salmoria et al., who analysed patients with stage D or stage E midpalatal suture maturation, found larger suture opening at both ANS and PNS for stage D patients compared to stage E patients[21]. Ngan et al. assessed MPSE at levels of the middle of the palate, canine, first and second premolars, first molar, nasal floor and palatal floor. Expansion ranged from 2.6mm at the middle of the palate to 3.7mm at the first premolars[40]. Storto et al. also reported significant MPSE at levels of the first premolar (3.6mm, $p < 0.001$) and first molar (3.9mm, $p < 0.001$)[42]. Zong et al. reported MPSE immediately after expansion, measured on coronal slices at the nasal (2.8 ± 1.5mm) and palatal floor (3.3 ± 1.8mm). In addition, MPSE was measured on axial slices at the anterior (3.1 ± 1.6mm) and posterior (3.3 ± 1.7mm) screw insertion sites[43]. To analyse the relation between the amount of MPSE and midpalatal suture maturation, Oliveira et al.[a] divided their sample into three groups: more than 1mm MPSE, less than 1mm MPSE or failure of MPSE. The authors reported on a negative correlation between the amount of MPSE and midpalatal suture maturation[35].

Expansion parallelism

Cantarella et al. assessed parallelism of MPSE in the sagittal and transversal plane. The authors found symmetrical anteroposterior expansion, in which expansion at PNS (4.3mm) was 90% of expansion at ANS (4.8mm)[23]. Similar results were reported by Bud et al.[b], who found that expansion at PNS was 85% of expansion at ANS, and Nguyen et al., who found 81.8% PNS expansion in respect to ANS expansion[37,48]. On postexpansion axial CBCT images, Colak et al. measured the angle at the convergence of two lines drawn between the right and left ANS and PNS. A mean angle of 0.6° (range: -0.8° – 1.3°, $p = < 0.0001$) was found. Though significant, the authors reported on a remarkably parallel expansion[26]. Elkenawy et al. reported an opening of 5mm at ANS and 4.8mm at PNS, resulting in 96% anteroposterior parallelism. In the transverse plane, 50% of patients exhibited asymmetrical expansion, which was defined as an ANS deviation >1.1mm[27]. Cantarella et al. found asymmetrical transverse expansion as well; on average, one half of the ANS moved 1.1 ± 1.0mm more than the contralateral half[23]. Almaqrami et al.

reported on asymmetrical expansion in 23 of 49 included patients (46.9%). Asymmetry was defined as >1.0mm difference in right and left transverse expansion[52].

Nasal- cavity and floor changes

Changes in nasal cavity width (NCW) were analysed on PA cephalograms[31,38] and CBCT coronal slices[19,30,32,34,39,42,45,46,51]. Choi et al. found that, more than three years after expansion, the increase in NCW of 0.8 mm (95% CI: 0.3-1.3, $p = 0.016$) was still significant[38]. Lim et al. found similar results: despite significant relapse of 0.4 ± 0.4mm ($p < 0.01$), the increase in NCW of 1.3 ± 0.8mm ($p < 0.01$) at level of the first molar was still significant one year after expansion[30]. Li et al.[b] (2.3 ± 1.2mm, $p < 0.001$) and Park et al. (1.4 ± 1.0mm, $p = 0.000$) observed significant increases in NCW increase as well[31,39]. Li et al.[a] found significantly more NCW increase at level of the first molars with bicortical screws (3.3 ± 1.1mm) compared to monocortical screws (2.1 ± 1.0mm, $p = 0.002$)[45]. Moreover, Jesus et al.[a] found significant NCW increases at levels of the canine and first molars[32]; Jia et al., Storto et al. and Oliveira et al.[b] found significant NCW increases at levels of the first premolars and first molars[19,34,42].

Nasal floor width (NFW) was assessed on CBCT coronal slices[30,32,39,44]. Similar to NCW, the NFW increase of 1.6 ± 1.0mm ($p < 0.01$) at level of the first molar was stable after one year, despite a significant relapse of -0.6 ± 0.7mm ($p < 0.01$)[30]. Li et al. found an increase of 2.3 ± 1.2mm within three months after expansion[39]. Jesus et al.[a] separately analysed NFW changes at levels of the canine (3.0 ± 1.3, $p < 0.001$) and first molars (3.5 ± 2.0, $p < 0.001$)[32].

Zygomaticomaxillary and midfacial effects

In depth analysis of changes to the zygomaticomaxillary complex was performed by five studies[24,25,27,28,41]. Cantarella et al.[b] analysed horizontal changes in the zygomaticomaxillary complex on axial CBCT images. The authors reported significant, lateral displacements of the maxillary and zygomatic bones and the whole zygomatic arch ($p < 0.0001$). Center of rotation for the zygomaticomaxillary complex was near the proximal portion of the zygomatic process of the temporal bone[25]. On coronal CBCT images, Cantarella et al.[a] also found outward rotations, with the center of rotation near the frontozygomatic suture[24]. Significant left and right lateral displacements of the zygomaticomaxillary complex were observed by Paredes et al. as well ($p < 0.0001$), measured on coronal CBCT images[28]. Song et al. analysed changes in the zygomaticomaxillary complex on CBCT in three dimensions: x, for horizontal changes, y for anteroposterior changes and z for vertical changes. Changes were analysed using the 3D coordinates of multiple anatomical landmarks. In the coronal plane, a pyramidal shaped expansion pattern was observed, indicating at downward and lateral displacements of the zygomaticomaxillary complex.

Forward and downward displacements of the zygomaticomaxillary complex were found in the sagittal plane[41]. Next to changes of the zygomaticomaxillary complex, significant width increases at the level of the zygomatic bone[24,25,31,39,41,45,46], temporal bone[39,45,46] and infra-orbital foramina[34] were reported.

Airway effects

An overview of airway effects can be found in **Table 5.**

Table 5. Overview of airway effects.

Author	Year	Sample size	Outcome assessment technique	Outcome assessment time points	Reported outcome changes (volume: mm^3, angle: °)	
Kim et al.	2018	14	CBCT	T0: Before expansion T1: Immediately after expansion *(mean: 10.71 days, range 0–35)* T2: One year after expansion *(mean: 14.0 months, range 12.0–15.3)*	T1-T0 NCV: 1061.6 ± 613.9* NPV: 513.3 ± 727.8 NCV+NPV: 1575.0 ± 881.8*	T2-T0 NCV: 1710.2 ± 881.6* NPV: 942.4 ± 821.0* NCV+NPV: 2652.6 ± 221.2*
				Relapse	T2-T1 NCV: 648.6 ± 827.2* NPV: 429.1 ± 817.2 NCV+NPV: 1077.7 ± 923.7*	
Li et al.[b]	2020	22	CBCT	3 months postexpansion	NCV: 2925.9 ± 4974.6* NPV: 734.9 ± 1045.1*	
Storto et al.	2019	20	CBCT	After expansion	NPV: 5777.6*	
Tang et al.[b]	2021	30	CBCT	3 months postexpansion	OPV: 962.6* NPV: 1342.8* HPV: -235.2	

Abbreviations: CBCT, conebeam computed tomography; CT, computed tomography; HPV, hypopharyngeal volume; LPV, laryngopharyngeal volume; NCV, nasal cavity volume; NPV, naspharyngeal volume; OPV, oropharyngeal volume.

Four studies assessed effects of MARME on the airway by calculating volumetric changes of the airway[29,39,42,47]. Kim et al. used CBCT images to assess volumetric changes in the nasal cavity and nasopharynx, as well as changes in the cross-sectional area at levels of the ANS (anterior), choanae (middle) and cervical vertebra 3 (posterior). Changes were analysed immediately and one year after expansion. A significant increase of the volume ($p < 0.05$) and cross-sectional area ($p < 0.05$) of the nasal cavity was seen immediately after expansion, with an additional increase one year after MARME. No significant change in the volume of the nasopharynx was seen after expansion. However, one year after expansion, the nasopharyngeal volume was significantly increased ($p < 0.05$) compared to the baseline volume. It was hypothesized that this occurred due to adaptation of the lateral walls of the nasal cavity[29]. Li et al. used CBCT to calculate volumetric changes three months after MARME in the nasal cavity and at the nasopharyngeal, retropalatal, retroglossal and hypopharyngeal areas. Significant increases of the nasal cavity volume ($p = 0.014$) and nasopharyngeal volume ($p = 0.003$) were observed[39].

In order to analyse respiratory muscle strength, nasal inspiratory peak flow and oral expiratory peak flow, Storto et al. performed respiratory tests before, immediately after and five months after MARME. Respiratory muscle strength was assessed by measuring the maximum inspiratory pressure (MIP) and maximum expiratory pressure (MEP). MIP showed a significant increase five months after expansion ($p < 0.05$). MEP significantly increased immediately after expansion ($p < 0.05$), but this increase was not retained five months after expansion. Nasal inspiratory peak flow and oral expiratory peak flow both significantly increased immediately and five months after expansion ($p < 0.05$). Moreover, nasopharyngeal airway volume increased significantly ($p < 0.05$)[42].

After MARME, Tang et al.[b] observed significant increases of the oropharyngeal ($p = 0.043$) and nasopharyngeal volume ($p < 0.001$) and the minimum cross-sectional area of the upper airway ($p = 0.03$). Furthermore, aerodynamic characteristics of the upper airway after MARME were assessed. The authors observed significant decreases in airway resistance during inspiration (-26.8%, $p < 0.001$) and expiration (-24.7%, $p = 0.001$)[47].

Soft tissue effects

Four studies analysed facial soft tissue changes after MARME[20,22,32,48]. Abedini et al. used 3D-stereophotogrammetry to create soft tissue meshes before, right after and one year after expansion with MARME. Nine manually labelled facial landmarks were defined: four at the inner and outer corners of both eyes; one on the nose tip; one on the nose base; two in the cheek areas and one centrally on the chin. The authors generated average 3D-models at each time point. The significance of displacement in different facial areas was analysed on p-maps and the magnitude and direction of displacement on vector maps. Significant lateral and forward changes ($p < 0.05$) were seen in the cheek areas and in the paranasal area. Changes in the cheek areas were of greater magnitude: 2.5 ± 0.4mm on the right side and 3.0 ± 0.5mm on the left side, compared to 1.4 ± 0.4mm in the paranasal area. The changes were stable after one year retention[22]. Lee et al. used 3D-stereophotogrammetry as well to analyse the impact of MARME on the nasal soft tissue directly after termination of expansion. The authors defined ten soft tissue landmarks, covering the pronasale, subnasale and the areas around the alar and inferior nostrils. In addition, the nasal volume was measured. 3D vector changes of the landmarks, horizontal distances between landmarks and changes in the nasal volume were analysed. Significant changes in the nasal region were observed ($p < 0.001$), with the nose tending to widen, move forward and downward. Next to this, the nasal volume showed a significant increase[20]. Nguyen et al. superimposed soft tissue reconstructions of pre-expansion CBCTs on postexpansion CBCTs to analyse soft tissue changes in the midfacial area. Soft tissue landmarks were placed on the subnasale, alar curvature points, midpoint of the philtrum, labrale superius, right and left cheilion and two cheek points. Significant lateral and forward changes of the alar curvature points and cheek points (all $p = 0.000$) were observed. Displacements in the cheek area were higher than in the paranasal (alar) area[48]. Jesus et al.[a] analysed widening of the nasal soft tissue on facial soft tissue reconstructions derived from CBCT scans. The authors measured the most lateral points on the nose wings before and after MARME and found a significant width increase of 2.0 ± 0.6mm ($p < 0.001$)[32].

DISCUSSION

The current systematic review provides a literature overview on MARME. A total of 32 articles were included, of which one study met the criteria for level 2 evidence of the OCEBM criteria. All other studies met the criteria for level 4 evidence of the OCEBM criteria. The included studies mainly consisted of populations with a mean age around 20 years old. In this group of patients, there is sufficient evidence that MARME can secure basal bone expansion. Significant skeletal, dental, upper airway and soft tissue effects were observed, but long-term outcomes are scarce. Results of MARME performed in older patients were limited and thus no conclusions can be drawn regarding effects in older patients. Moreover, a lack of outcomes on patient experience and satisfaction, clinical improvements, and treatment related difficulties was found.

Dental effects

In general, significant increases were seen in interdental width for canines, premolars and molars. Most studies had a short follow-up period, performing measurements directly after or within three months after expansion[19,31,32,40,42-44,51]. Two studies analysed stability and relapse of these increases with a longer follow-up period: Choi et al. had a follow-up of more than three years, while Lim et al. reported outcomes one year after expansion. In the first period after expansion and following orthodontic alignment, significant relapse was observed. Nevertheless, width increases remained significant after one year and more than three years[30,38]. Taking midpalatal suture maturation in account, Salmoria et al. reported on a larger interdental width increase for the first molars in stage D midpalatal suture maturation, compared to stage E patients, but similar interdental width increase for the premolars[21].

Thus, MARME can be considered effective for achieving stable dental width increases, which are required for achieving a stable and functional occlusion. Changes that appear after a longer follow-up may need to be interpreted cautiously, as patients have had orthodontic treatment in conjunction to MARME. Therefore, the changes may not solely be attributed to relapse in MARME expansion.

Dentoalveolar tipping and periodontal effects

Tipping of anchored teeth was common: especially the first molars showed significant tipping within three months after expansion[19,21,31,34,36,40,42-45]. The importance of bicortical miniscrew implantation was emphasized by Li et al; monocortical miniscrews produced more unwanted dentoalveolar side effects such as dental and alveolar tipping[45]. After conclusion of expansion, Salmoria et al. found no significant differences in inclination of the first molars and first premolars in patients with stage D or stage E midpalatal suture maturation[21]. Lim et al. reported outcomes with a longer follow-up. After initial buccal tipping of the first molar, no significant increase in tipping was seen after one year. In contrast, one-year after completion of expansion, more tipping of the alveolar bone was observed. Alveolar bone movement seemed to occur more slowly than the tooth movement, suggesting the alveolar bone underwent remodeling[30]. Alveolar tipping is inevitable, because the maxillary center of rotation is higher than the miniscrew insertion sites[24,25,30,43]. Dental tipping cannot be dissociated from alveolar tipping, and therefore, a certain degree of dental tipping is inevitable as well[31]. The longest follow-up period was one year, which may be insufficient to adequately address stability of the changes. Moreover, tipping should be seen in light of the design of the MARME appliance. Changes in appliance design may require different anchorage locations. This may influence the rotational fulcrum and result in different presentations of dental or alveolar bone tipping.

Regarding periodontal changes, significant losses in buccal alveolar bone thickness and buccal alveolar crest height were seen[19,30,31,37,40,44,51]. Loss of buccal alveolar bone thickness is a common consequence of RME[53]. According to Park et al., loss in buccal bone thickness was similar to SARME[31]. A decrease in buccal alveolar crest height may be caused by dental tipping and can eventually result in gingival recession. However, no significant gingival recession and no significant difference in clinical crown heights were observed during and after MARME[30,38]. Additionally, recovery of the buccal alveolar bone might occur over a longer period of time, which was not assessed in the included studies.

Nevertheless, Lim et al. warn for the possibility of alveolar dehiscence after MARME[30]. Similarly, Moon et al. emphasized that MARME can decrease buccal bone thickness[44].

It can be concluded that MARME inevitably leads to a certain degree of dental and alveolar tipping. However, long term stability was not addressed in included studies. Standardized measurements are necessary to compare tipping between studies and devices. Care should be taken in patients with thin alveolar bone and compromised periodontal conditions, as MARME could induce alveolar dehiscence. Subsequently, periodontal conditions should be monitored in patients treated with MARME.

Skeletal effects

Significant skeletal width increases after MARME were observed for NCW, NFW, maxillary width, alveolar bone width and first molar width. At least for NCW, NFW, maxillary width and alveolar bone width, skeletal increases were stable after one year and more than three years after debonding of the MARME appliance[30,38,46]. Choi et al. found that the amount of basal bone expansion and stability of MARME was comparable to SARME[38,54]; Ngan et al. found skeletal expansion similar to SARME[40,55]. Increase in nasal cavity and floor width may contribute to airway improvements, whereas increases in maxillary width are required for achieving an adequate transverse maxillary dimension.

Most studies excluded patients in whom splitting of the midpalatal suture failed. Splitting success rates varied from 71.4% to 100%. (*Table 2*) Splitting of the midpalatal suture is crucial for realizing expansion and often considered a limiting factor in skeletally mature patients. Included studies propose evidence that MARME can be used to split the midpalatal suture, at least in younger patients, thus offering a nonsurgical alternative to SARME in skeletally mature patients. Oliveira et al.[a] analysed factors associated with successful splitting of the midpalatal suture. The authors found MARME to be less successful in patients aged 30 years or older, but only five patients aged 30-39 years were analysed. In this group, MARME succeeded in one patient[35]. Salmoria et al. found more MPSE and diastema opening in patients with stage D midpalatal suture maturation (aged 18.8 ± 0.6 years) compared to older stage E patients (mean age 31.0 ± 5.2 years)[21]. Similarly, Jesus et al.[b] reported a lower MARME success rate in older patients with advanced bone maturation[33]. Bud et al. dealt with advanced midpalatal suture maturation by applying corticopuncture therapy prior to MARME[36,37]. In other studies, information on effects of MARME in older patients or different treatment modalities for this group of patients remained limited.

Amount of MPSE was assessed at multiple levels, including the premolars and molars[19,40,42], nasal and palatal floor[40,43] and at the miniscrew insertion sites[43]. MARME was found to induce a relatively parallel anteroposterior expansion[23,26,27,31,37,40,48,52]. During expansion, the pterygopalatine suture seems to be a center of resistance and loosening this suture may be beneficial to a parallel anteroposterior expansion. This way, a v-shaped expansion pattern, in which the anterior part is expanded more than the posterior part, can be avoided[43,56]. Two studies demonstrated that splitting of the pterygopalatine suture can be achieved with MARME and thus without an osteotomy[23,26]. Li et al. assumed opening of the pterygopalatine sutures as well, because an increase in width between the lateral pterygoid plates was observed. The authors report on placing the posterior two miniscrews close to the pterygopalatine suture, to overcome initial resistance here[45]. In the transverse plane, MARME was found to induce asymmetrical expansion at the ANS[23,27,52]. Asymmetrical expansion has been observed in SARME as well[57]. Regarding the zygomaticomaxillary complex, a forward and downward movement was observed, as well as significant width increases at the level of the zygomatic and temporal bone[25,27,31,39,41,46].

Thus, skeletal changes at multiple levels are induced by MARME, resulting in significant width increases in the nasal, maxillary, zygomatic and temporal regions. Using MARME, splitting of the midpalatal suture can be achieved in a relatively noninvasive fashion. Furthermore, splitting of the pterygopalatine suture was observed. Nevertheless, long-term stability of the skeletal changes are still unknown.

Airway effects

Overall, enlargement of the upper airway after MARME was observed. Kim et al. presented changes one year after expansion. Significant increase of the nasal cavity volume (15.4%) and of the nasopharyngeal volume (10.5%) were found. Volumetric increase partially happened during retention[29]. Five months after expansion with MSE, Storto et al. found an increase in the nasopharyngeal volume of 26%[42]. This difference may be due to the appliance; Garcez et al. addressed the ability of MSE to promote expansion in the posterior and superior aspects of the nasal cavity, which subsequently may lead to improved respiratory function[58]. This was addressed by Storto et al. as well, who also analysed respiratory function after MARME. Skeletal expansion by MARME appeared to improve airway flow and respiratory muscle strength, consequently improving respiratory function in terms of nasal inspiratory- and oral expiratory peak flow. Improvements were stable after five months retention and comparable to results achieved with SARME and conventional RME in younger patients[42]. Tang et al.[b] also analysed clinical effects of MARME on respiratory functions. Significant decreases of airway resistance were observed. The authors report that airway improvements after MARME might be beneficial for patients suffering from obstructive sleep apnea syndrome (OSAS)[47]. It can be concluded that MARME promotes a stable increase of the upper airway volume.

There are indications that these increases improve respiratory functions. As previously addressed, a parallel skeletal anteroposterior expansion after MARME was observed and the posterior expansion may contribute to increased nasal cavity- and floor volumes and improved respiratory functions. However, other clinical impacts such as OSAS, and long-term effects are unknown.

Facial soft tissue effects

Short-term soft tissue effects of MARME were addressed by three studies[20,32,48]. Jesus et al.[a] described significant widening of the nose directly after MARME expansion[32]. Lee et al. found significant changes in facial soft tissue areas, mainly around the nose as well. The nose tended to widen and move forward and downward. Width increases were smaller compared to SARME, possibly because of less skeletal expansion in MARME[20]. Forward and lateral displacements of the nose (alar curvature) and cheeks were observed by Nguyen et al. as well. These movements correlated with the amount of expansion at the ANS and PNS[48]. Abedini et al. reported similar soft tissue changes: statistically significant soft tissue changes after MARME were found in the paranasal, upper lip, and cheek areas. Furthermore, forward and horizontal changes were observed, which are in correspondence to bony changes in the zygomaticomaxillary complex described by Cantarella et al. and Song et al.[25,41]. Transverse facial soft tissue changes were found to be asymmetrical, which was in concordance with the asymmetrical skeletal expansion reported by Elkenawy et al. and Cantarella et al.[25,27]. Changes were stable at one-year follow-up[22]. Ultimately, MARME induces soft tissue changes, particularly in the paranasal area. Patients should be informed on the soft tissue effects of MARME, which may affect aesthetics. Contradictory to conventional RME, in which soft tissue changes can be overshadowed by normal growth of the younger patients, MARME is also performed in non-growing patients, in whom changes can be more permanent. As aesthetical outcomes are subjective, future studies should incorporate patient reported outcomes, which are lacking in the current literature.

Complications

Complications of MARME were scarcely described. Choi et al found that 5% of miniscrews dislodged during expansion and 13% showed clinically acceptable mobility; all other miniscrews remained stable until the retention period. Moreover, the authors found irritation of the mucosa, which can be prevented by accurate placement of miniscrews and scrupulous oral hygiene[38]. Bud et al.[a] reported on six patients (22.2%) who showed hypertrophy of the palatal mucosa, which was associated with ulcerations, erythema, itching, and discomfort. Necrosis of the palatal mucosa was not observed[36]. In patients undergoing corticopuncture therapy, Bud et al.[b] found no postoperative bleeding, swelling or sepsis. Healing at level of the corticotomy was observed as well[37]. Tang et al.[a]

excluded three patients because of loose mini-screws[46]. In comparison to a tissue bone-borne C-expander group, Moon et al. found significantly more buccal bone dehiscence in MARME patients (4.2% vs. 31.3%, $p = 0.001$) and therefore advised on using a C-expander in older patients or patients with poor periodontal support[44]. In the study by Zong et al., transverse maxillary deficiency remained in seven patients after MARME. Furthermore, in three patients, the miniscrews showed inclination on the post-MARME CBCT[43].

Thus, in the current literature, complications in MARME are minimally reported. Reported complications seem to be minor and manageable. Nevertheless, more studies on complications in MARME are required.

Patience experience and satisfaction

No studies reported results on patient experience or satisfaction. Zong et al. addressed that all patients tolerated pain during expansion, but also disclosed mild to moderate pain in more than half of patients after expansion. The authors advised on strict sterilization of the miniscrews before implantation, parallel implantation of the miniscrews and flushing the palatal insertion site of the miniscrews with water as much as possible[43]. Li et al. reported on excluding patients who stopped MARME treatment because of swelling of the palatal mucosa or intolerance to the MSE[45]. Moon et al. reported on patients skipping one day of expansion in case of excessive stress[44]. Information on patient experience and satisfaction in respect to MARME are factors that may influence patients' choice of treatment, but are too scarcely described in current literature.

Comparison to SARME

Two studies incorporated a retrospective comparison between MARME and tooth-borne SARME. MARME patients were different in the two studies, but the SARME sample was the same for both studies[32,34]. Where tooth-borne SARME induced more expansion in the anterior nasal cavity (V-shaped expansion), MARME induced more uniform increases in both anterior and posterior parts of the nasal cavity[32]. MARME induced a greater transverse maxillary expansion in the palate and maxillary basal bone compared to SARME; expansion in the alveolar process did not differ. Increase in IFMW and IFPMW were greater for SARME, but more tipping of anchored teeth and of the alveolar process were observed for SARME as well. The authors also report on greater nasal cavity expansion for MARME, but no volumetric measurements were performed[34]. Other studies compared MARME to SARME based on results from the literature.

SARME has proven to induce stable skeletal and dental expansion[59]. Similarly, MARME seems to adequately ensure skeletal and dental expansion. Nevertheless, measurements regarding dental and alveolar tipping in MARME are too heterogeneous to comprehensively compare to SARME, and outcomes of stability after MARME are scarce. In order to properly compare MARME and SARME, randomized studies are necessary, preferably with long-term follow-up.

In conclusion, in the current cohort of patients aged around 20 years old, MARME seems suitable for realizing transverse maxillary expansion, resulting in adequate dental and skeletal expansion. However, there is limited knowledge on long-term outcomes. MARME promotes an increase in upper airway volume, but long-term outcomes and clinical relevance are unknown. Facial soft tissue changes are induced by MARME, mainly in the paranasal area. Patient-reported outcomes regarding aesthetical changes after MARME were not evaluated and should be incorporated into future studies. In the current systematic review, most included studies were of low quality. In the periodontally compromised patient, MARME should be employed with caution and subsequently, periodontal conditions of patients treated with MARME should be monitored. Future studies should include greater sample sizes and further investigate MARME in older patients, to address treatment options and effects in this group of patients. Besides studies comparing skeletal, dental, soft tissue and upper airway effects between MARME and SARME, new studies on complications, patient experience and satisfaction, and long-term outcomes after MARME are necessary.

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APPENDIX I: SEARCH STRATEGIES.

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(((‘nonsurgical invasive therapy’/de OR ‘minimally invasive procedure’/exp) AND (‘palatal expansion’/de OR ‘expansion screw’/de OR ‘palatal expander’/de OR ‘trans-palatal distractor device’/de)) OR (MARPE OR MARME OR ((mini* OR micro*) NEAR/3 (screw* OR implant*) NEAR/9 (palat* OR maxilla*) NEAR/9 (expan* OR distract*)) OR ((nonsurg* OR non-surg* OR mini*-invas*) AND (transverse*-deficien* OR (palat* OR maxilla*) NEAR/3 (expan* OR hypoplasia* OR distract*)))):ab,ti,kw)

Medline (Ovid)

((Minimally Invasive Surgical Procedures/ AND Palatal Expansion Technique/) OR (MARPE OR MARME OR ((mini* OR micro*) ADJ3 (screw* OR implant*) ADJ9 (palat* OR maxilla*) ADJ9 (expan* OR distract*)) OR ((nonsurg* OR non-surg* OR mini*-invas*) AND (transverse*-deficien* OR (palat* OR maxilla*) ADJ3 (expan* OR hypoplasia* OR distract*)))).ab,ti,kw.)

Web of Science Core Collection

TS=(((MARPE OR MARME OR ((mini* OR micro*) NEAR/2 (screw* OR implant*) NEAR/9 (palat* OR maxilla*) NEAR/9 (expan* OR distract*)) OR ((nonsurg* OR non-surg* OR mini*-invas*) AND (transverse*-deficien* OR (palat* OR maxilla*) NEAR/2 (expan* OR hypoplasia* OR distract*))))))

Cochrane Central Register of Controlled Trials

((MARPE OR MARME OR ((mini* OR micro*) NEAR/3 (screw* OR implant*) NEAR/9 (palat* OR maxilla*) NEAR/9 (expan* OR distract*)) OR ((nonsurg* OR non-surg* OR (mini* NEXT/1 invas*)) AND ((transverse* NEXT/1 deficien*) OR (palat* OR maxilla*) NEAR/3 (expan* OR hypoplasia* OR distract*)))):ab,ti,kw)

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“mini|micro screw|implant|screws|implants”|microscrew|microimplant|miniscrew|microscrews|microimplants|miniscrews|nonsurgery|non-surgery palatal|maxilla|maxillary expansion|distraction|expanded|distracted|hypoplasia

RETROSPECTIVE CLINICAL STUDIES

4

Three-dimensional dento-skeletal effects of mandibular midline distraction and surgically assisted rapid maxillary expansion: A cone beam computed tomography analysis

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Submitted J Craniomaxillofac Surg.

ABSTRACT

To provide 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. All included 30 patients had undergone MMD (20 bone-borne MMD; 10 tooth-borne MMD). Twenty bone-borne MMD and 8 tooth-borne MMD patients had simultaneously undergone tooth-borne SARME. Cone beam computed tomography (CBCT) records were taken pre-operative (T1), immediately post-distraction (T2) and 1 year post-operative (T3). At T1 vs T3, canine ($p=0,007$) and first premolar ($p=0,005$) showed significant expansion on tip level for tooth-borne MMD. This was however not significant on apex level, indicating tipping. At T1 vs T3, mean expansion on canine, first premolar and first molar tip level remained significant ($p<0,05$) for bone-borne and tooth-borne MMD, and for tooth-borne SARME. Bone-borne MMD showed a parallel distraction gap, whereas tooth-borne MMD showed a V-shape. No significant ($p>0,05$) changes were seen in ramal angle and inter condylar distance for MMD, despite significant ($p=0,017$) inter condylar axes increase for bone-borne MMD. Tooth-borne SARME combined with bone-borne MMD showed (reverse) V-shape maxillary widening. In conclusion, three-dimensional CBCT analysis for dento-skeletal effects of bone-borne vs tooth-borne MMD and tooth-borne SARME showed stable dento-skeletal effects at T3.

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[1,2]. With these camouflage techniques, high relapse rates were observed in the long-term[3]. At 1 year of age the mandibular symphysis closes, making surgery necessary to achieve bony expansion[4,5]. Midpalatal suture expansion without surgery is predictable until approximately the age of 15[6]. With the introduction of distraction for the facial skeleton in the early 1990s, new treatment options became possible[7,8].

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[9,10]. For transverse maxillary discrepancies, surgically assisted rapid maxillary expansion (SARME) is a well-known stable surgical technique[11,12]. Some specific cases require a combination of MMD and SARME, which is termed bimaxillary expansion (BiMEx)[13]. Regarding distraction, there are various types of distractors such as tooth-borne, bone-borne or a combination of both (hybrid). For the mandible, after performing an osteotomy 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 rotational, translational and horizontal movements. The biomechanical effects of the different types of distractors may influence the distraction and have their influence on the TMJ[14-16]. Until now research on dento-skeletal effects of MMD using 3D imaging analysis techniques has been reported scarcely[17,18], and is by and large performed using conventional methods like dental cast models and posterior-anterior cephalograms[9,10,19-21]. On the other hand, SARME is well reported using 3D imaging analysis techniques[22-29]. Little is known about the dento-skeletal effects of BiMEx using 3D imaging analysis techniques[13]. To our knowledge 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 (1) bone-borne vs tooth-borne MMD and tooth-borne SARME and (2) bone-borne vs tooth-borne MMD solitary. This information can assist orthodontists and oral and maxillofacial surgeons in their treatment planning of transverse mandibular and maxillary discrepancies.

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).

Patients

In this study, the following patients were included:

Patients who underwent bone-borne or tooth-borne MMD combined with tooth-borne SARME.

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 old.

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[14], combined with a bone-borne (© KLS Martin Group, Rotterdam Midline Distractor) or tooth-borne distractor (Hyrax, anchorage on first premolar and molar).

Regarding SARME, the surgical technique was according to Koudstaal et al.[12] combined with only a tooth-borne distractor (Hyrax, anchorage on first premolar and molar). Both surgical interventions were performed under general anesthesia.

CBCT records were taken at pre-operative (T1), immediately post-distraction (T2), and 1 year post-operative (T3).

CBCT analysis

CBCT scans (varied between 0,3 and 1 mm slice thickness) were performed at T1, T2 and T3. The data were analyzed using the software © Carestream Health, Inc. 2021, Vue Motion, version 12.2.1.4023. 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:

Bone-borne and tooth-borne MMD (**Fig. 1**), using coronal CBCT slices.
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).
Inter first molar distal apex distance (MANIFMAD).

Tooth-borne SARME (**Fig. 2**), using coronal CBCT slices.
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).
Inter first molar disto-buccal apex distance (MAXIFMAD).

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

Bone-borne and tooth-borne MMD (**Fig. 3**), using axial CBCT slices and 3D skeletal view.

Inter condylar distance (ICOND), from 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 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).

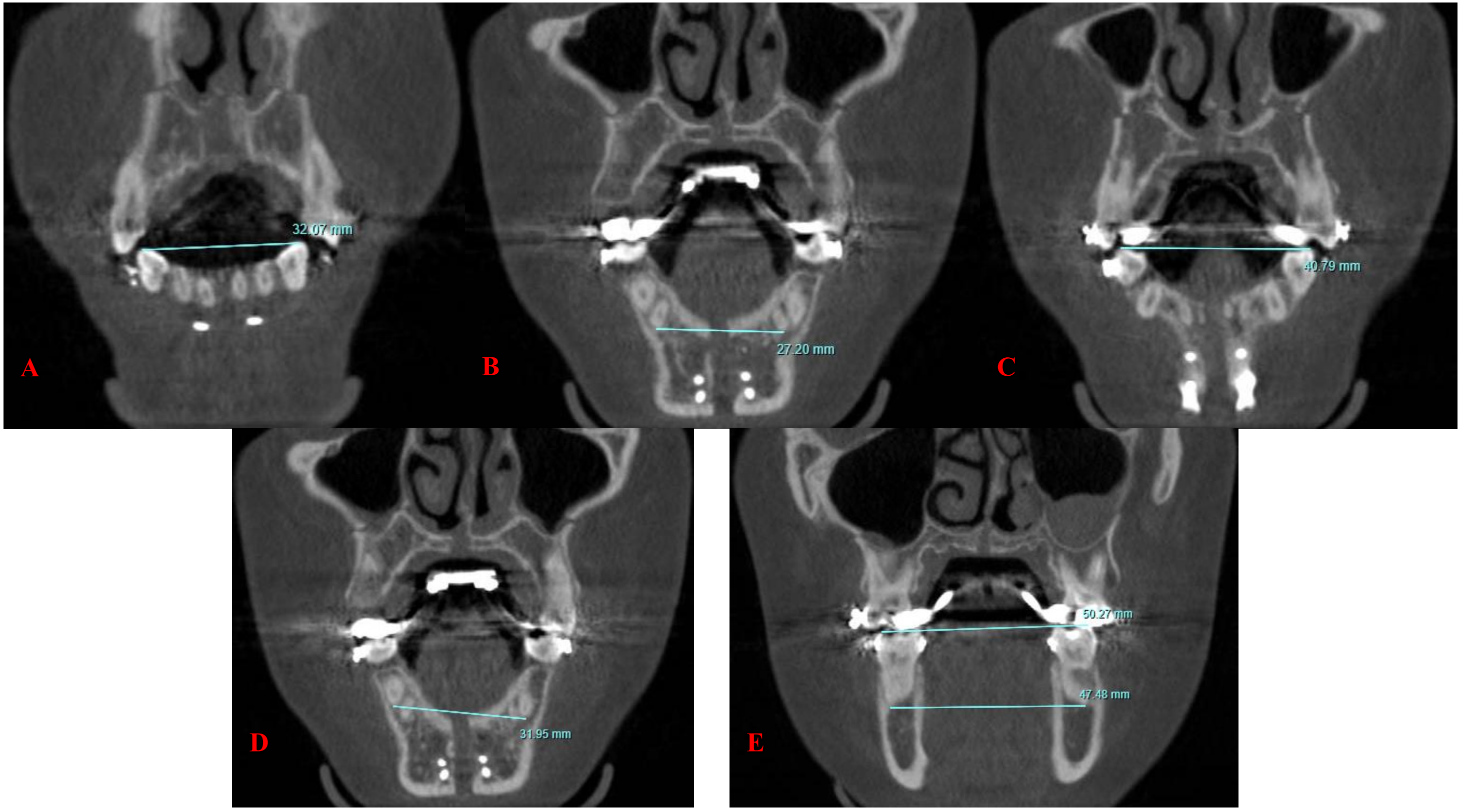

Fig. 1. Dental measurements regarding bone-borne vs tooth-borne MMD using coronal CBCT slices at T1, T2 and T3. A: MANICTD; B: MANICAD; C: MANIFPTD; D: MANIFPAD; E: MANIFMTD, MANIFMAD.

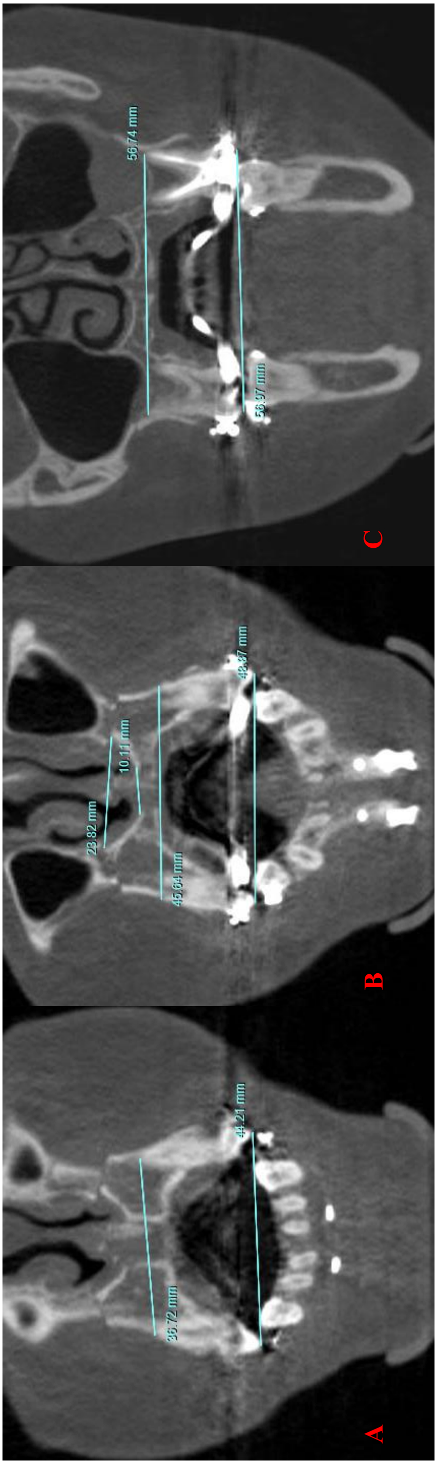

Fig. 2. Dental and skeletal measurements regarding tooth-borne SARME using coronal CBCT slices at T1, T2 and T3. A: MAXICTD, MAXICAD; B: MAXIFPTD, MAXIFPAD, MAXPALW, MAXPABW; C: MAXIFMTD, MAXIFMAD.

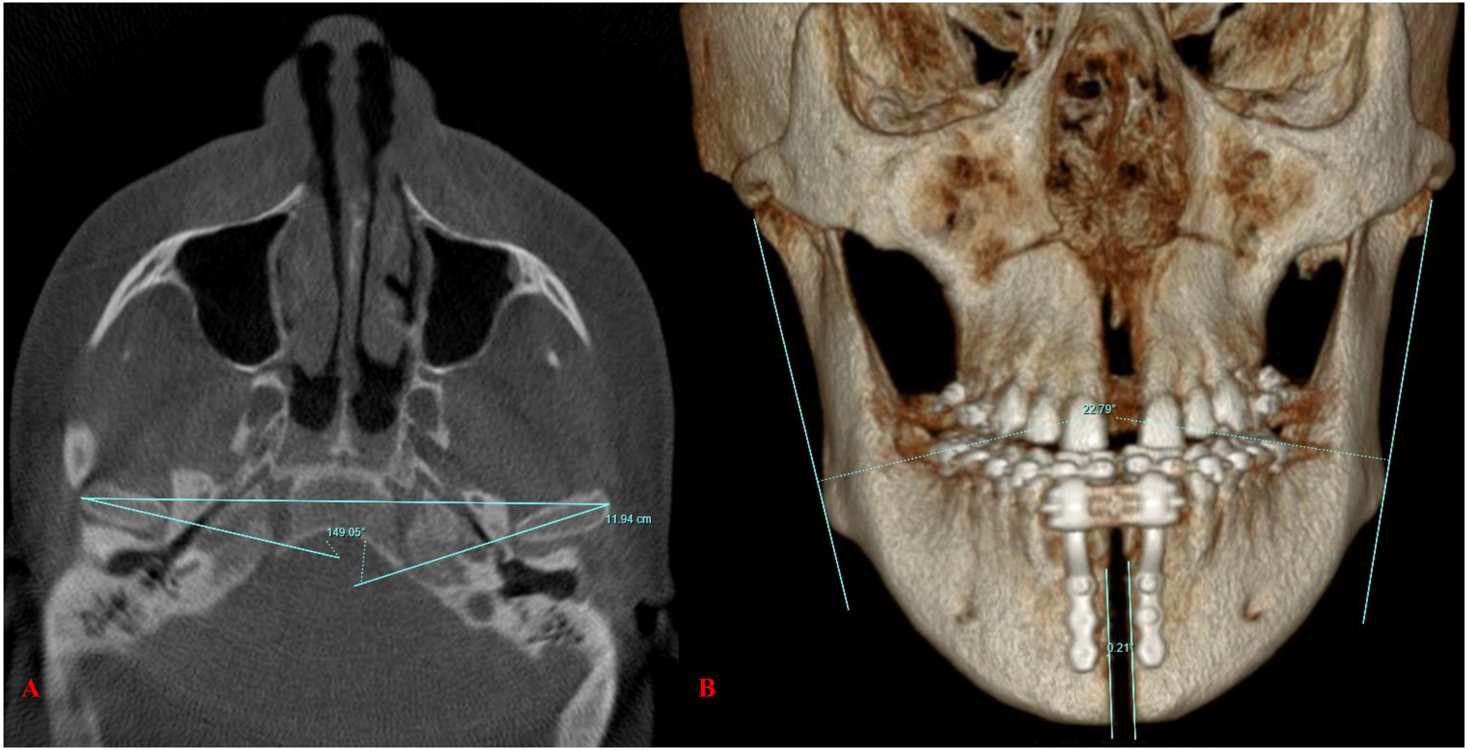

Fig. 3. Skeletal measurements regarding bone-borne vs tooth-borne MMD using axial CBCT slices and 3D skeletal view at T1, T2 and T3. A: ICOND, ICONA; B: RA, DGAPA (only at T2).

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.

Piriform aperture base width (MAXPABW), from lowest aspect of the piriform aperture to its counterpart.

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's 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 smaller than 0,05 was considered to be statistically significant. We followed the STROBE guideline for reporting of this study[30].

Reliability analysis

Inter- and intra-observer agreement was 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 author and third author 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[31].

RESULTS

Patients

In this study, 30 patients were included. All 30 patients had undergone MMD, of whom 20 patients with a bone-borne MMD and 10 patients with a tooth-borne MMD. All 20 bone-borne MMD patients and 8 out 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. See *Table 1* for the patient characteristics.

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

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:9M	6F:4M

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.

CBCT dental analysis

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*.

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*

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

	MANICTD *T1* mean +- SD	**MANICTD** *T2* mean +- SD	**MANICTD** *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.

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 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), while all other inter dental distances did not change significantly. At T1 vs T3 MANICAD and MANIFPAD did not change significantly, while MANICTD (p = 0,007) and MANIFPTD (p = 0,005) were increased significantly which indicate tipping. Only MANIFMTD and MANIFMAD were both increased significantly on 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 not significant anymore. 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.

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*.

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**

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

	MAXICTD *T1* mean +- SD	**MAXICTD** *T2* mean +- SD	**MAXICTD** *T3* mean +- SD	*T1* vs *T2*	*T2* vs *T3*	*T1* vs *T3*
	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.

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 not significant anymore indicating a more parallel wise expansion of the canines on 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 not significant anymore suggesting a more parallel wise expansion of the first molars on tip and apex level.

CBCT skeletal analysis

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

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.

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

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

	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 Fisher's exact test.

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).

Reliability analysis

ICC for each separate measurement is described 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.

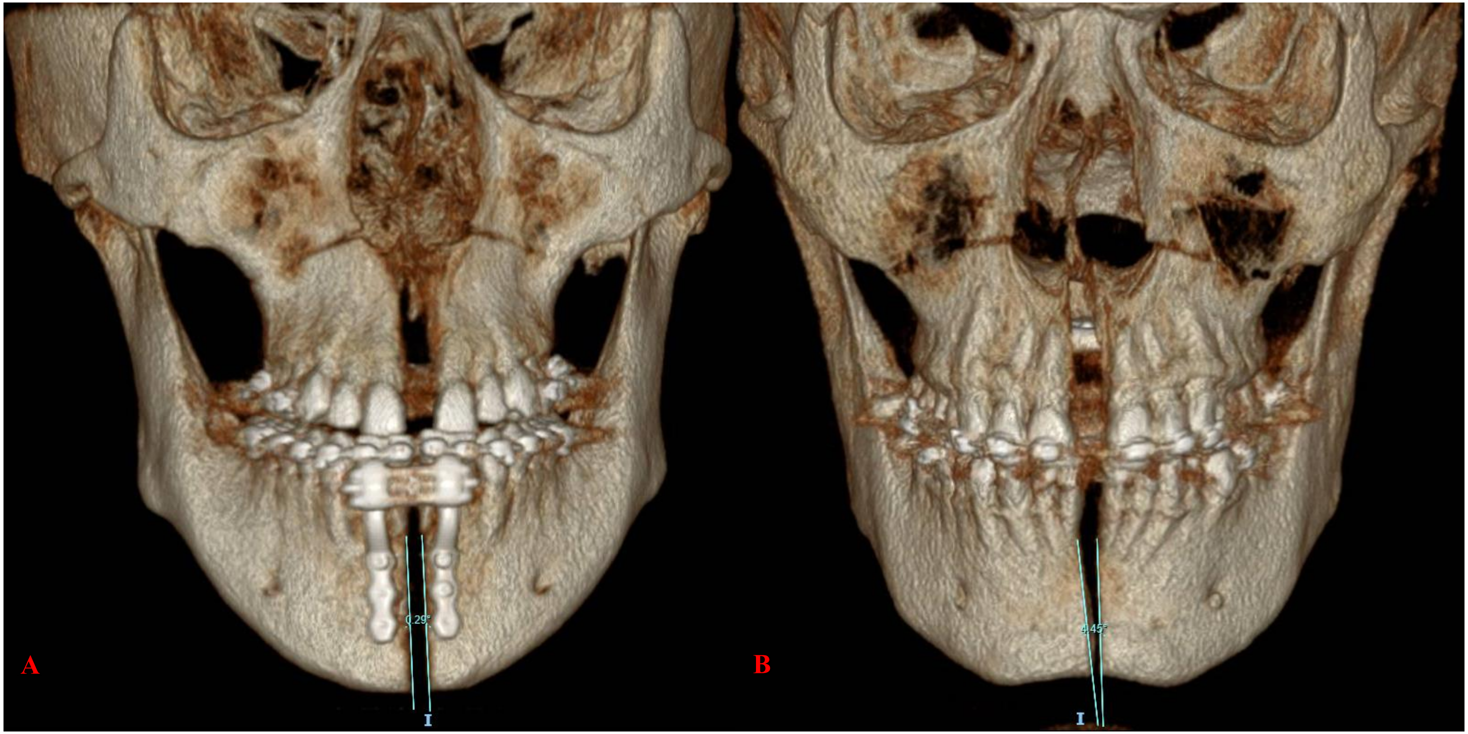

Fig. 4. Difference of DGAPA in the 3D skeletal view at T2. A: Bone-borne MMD; B: Tooth-borne MMD.

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.

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 at pre-operative (T1), immediately post-distraction (T2), and 1 year post-operative (T3) and analyzed as described in the materials and methods section.

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 our previous study[10].

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 (2,89 +- 2,39) vs mandibular inter canine apex distance (5,21 +- 2,51) at T3-T1, may be the result of the orthodontic treatment moving the 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, while mandibular inter canine tip distance (p = 0,007) and mandibular inter first premolar tip distance (p = 0,005) were increased significantly which indicate tipping. These results are broadly in line with Seeberger et al. indicating significant tipping of the (first) premolar due to the anchorage and distraction forces of the tooth-borne distractor[17]. 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 three months after surgery and before orthodontic treatment which is making comparison difficult. In our study no significant tipping of the (first) molar was observed for the tooth-borne distractor at T2-T1 and T3-T1. This could be also 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 dento-alveolar level. In contrast, the applied forces with the bone-borne distractor are at basal bone level resulting in no significant tipping (p = 0,247) of the (first) premolar at T3-T1 which indicate 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, distraction gap angle for bone-borne MMD (1,54 +- 1,93) vs tooth-borne MMD (3,02 +- 2,31) differed significantly (p = 0,040) indicating a more parallel distraction gap at basal bone level and without anterior mandibular skeletal tipping in the coronal plane for bone-borne MMD. This outcome is also indicating a V-shape 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 (p = 0,256) and tooth-borne MMD (p = 0,241). These outcomes are in line with Seeberger et al.[17], as they observed significant (p = 0,001) tipping of the mandibular corpus and no significant (p = 0,136) changes in inter condylar distance for tooth-borne MMD.

Theoretically, tooth-borne MMD applies distraction forces more posterolateral 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 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 (p = 0,7398) and ramal angle (p = 0,5514)[13]. Landes et al. observed a significant (p = 0,02) decrease (1,2 +- 0,8) in inter condylar distance for bone-borne MMD[18], however this outcome should be interpreted very carefully given the low number (nine) of patients included. In the same study, condylar angulation and vertical medial, cranial, and lateral distances to the fossa remain unchanged [18]. This is in contrast to our study as we observed significant (p = 0,017) increase in inter condylar axes for bone-borne MMD at T1 vs T3, which is indicating a condylar exorotation in the axial plane. Although it was not significant, it is remarkable that inter condylar axes was 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.

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 our previous study[11].

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.[29] 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. Hereby, it should be noted that their results were obtained three months after surgery and before orthodontic treatment which is making 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 this study, we observed significant increase in piriform aperture base width and piriform aperture lateral width at T1 vs T2. However, at T1 vs T3 only piriform aperture base width remained significantly increased when combined with bone-borne MMD ($p < 0,001$). This outcome is indicating a (reverse) V-shape 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[26,29]. In addition, Zandi et al. did not find any significant difference in skeletal tipping for bone-borne vs tooth-borne SARME[26].

Moreover, it should be noted that our findings regarding skeletal effects in the nasal region broadly correlate with our previous study regarding 3D soft tissue effects of bone-borne MMD and tooth-borne SARME[32]. We presented a significant mean increase of 2,20 mm in the inter-alar width (corresponding with piriform aperture lateral width) and a non-significant mean increase of 1,77 mm in the inter-alar curvature point width (corresponding with piriform aperture base width). 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 are suggesting that besides the observed hard tissue effects other factors could influence these soft tissue effects like 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 T3, 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 one year since the majority of the included patients underwent additional surgery directly after one year. Hereby, 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 our 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 our 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-shape anterior mandibular skeletal tipping in the coronal plane is remarkable for tooth-borne MMD. However, a long-term follow-up of tooth-borne vs a combination of tooth-borne and bone-borne (hybrid) MMD showed that both are a viable treatment options[33]. In addition, we presented already that bone-borne MMD is a proven clinical 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 presented study)[10].

Although bone-borne and tooth-borne MMD both are stable techniques to achieve transversal (dento-skeletal) expansion, the choice of distractor type is more depending 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[34] and do not need a second surgical procedure to remove. 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.

CONCLUSION

3D CBCT analysis for dento-skeletal effects of bone-borne vs tooth-borne MMD and tooth-borne SARME showed stable dento-skeletal effects after one year, showing to be reliable treatment options for transverse mandibular and maxillary discrepancies. The canine and (anchorage) first premolar showed significant tipping for tooth-borne MMD, and for tooth-borne SARME (anchorage) first premolar showed significant tipping when combined with bone-borne and tooth-borne MMD. Bone-borne MMD showed a more parallel wise distraction gap at basal bone level, whereas tooth-borne MMD showed a V-shape distraction gap indicating anterior mandibular skeletal tipping in the coronal plane and suggesting dento-skeletal tipping of the mandibular canine and first premolar. There were no significant changes seen in ramal angle and inter condylar distance for MMD, despite significant inter condylar axes increase for bone-borne MMD. For tooth-borne SARME, only piriform aperture base width remained significantly increased when combined with bone-borne MMD indicating a (reverse) V-shape widening of the nasal floor in the coronal plane (skeletal tipping). Orthodontists and oral and maxillofacial surgeons should be aware of these (dento-skeletal) differences when choosing the distractor type.

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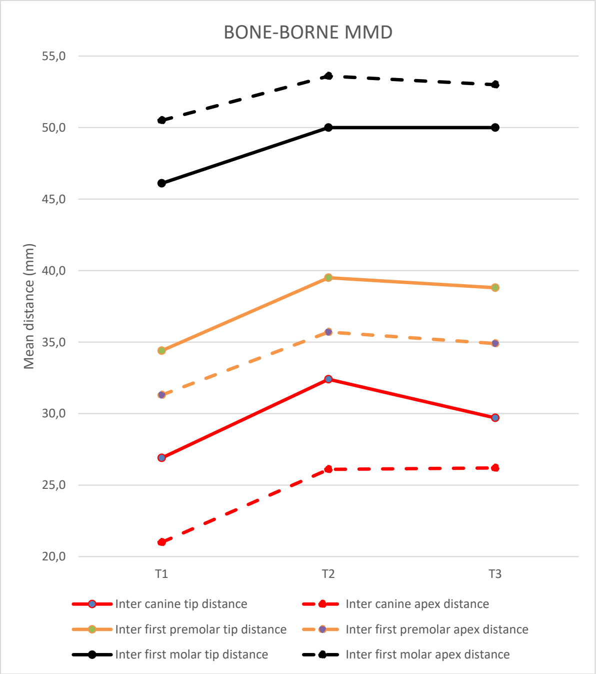
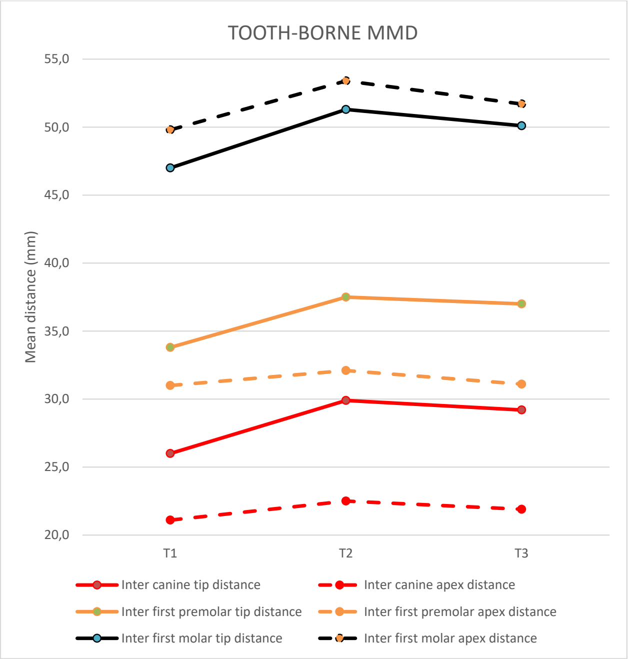
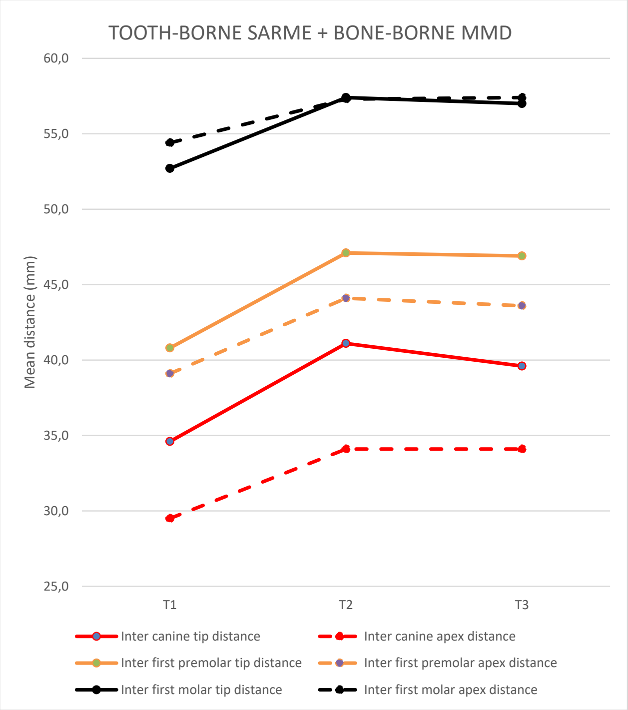
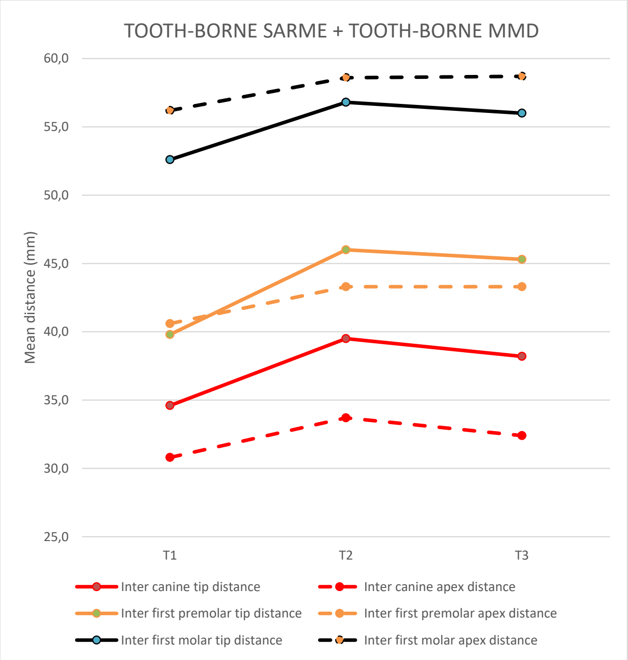


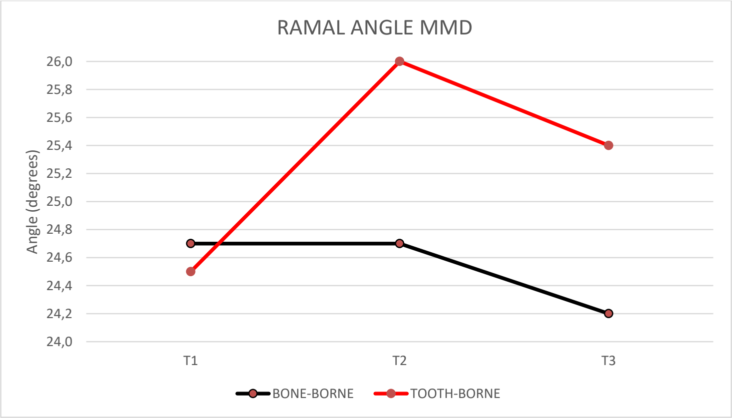


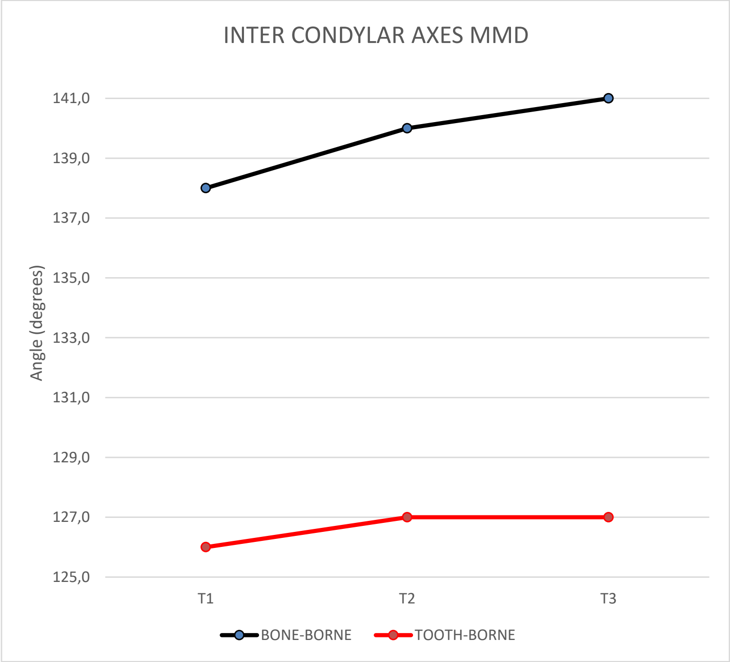
Appendix I. Bone-borne vs tooth-borne MMD, mean distance on tip and apex level.

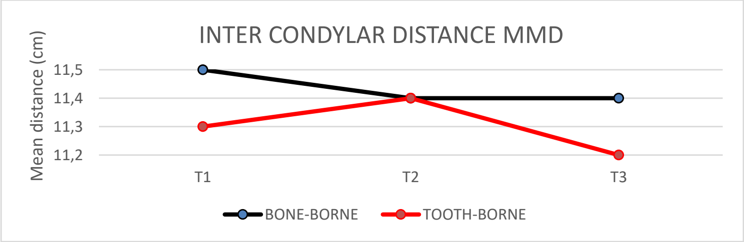




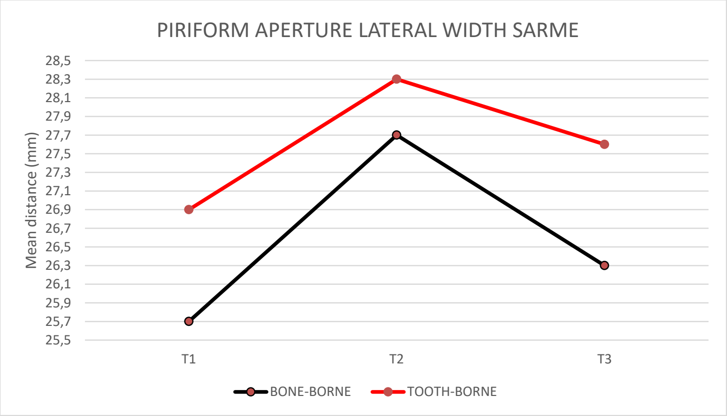
Appendix II. Tooth-borne SARME, mean distance on tip and apex level.

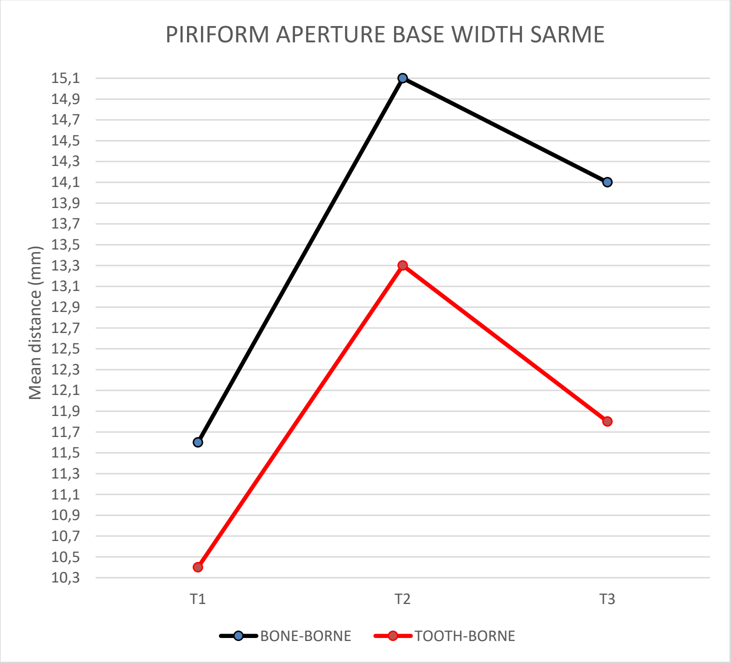






Appendix III. Bone-borne vs tooth-borne MMD, skeletal effects.





Appendix IV. Tooth-borne SARME, skeletal effects.

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Three-dimensional soft tissue effects of mandibular midline distraction and surgically assisted rapid maxillary expansion: An automatic stereophotogrammetry landmarking analysis

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ABSTRACT

Studies on mandibular midline distraction (MMD) are mostly performed using conventional research methods. Concerning surgically assisted rapid maxillary expansion (SARME), more research is conducted with three-dimensional techniques. Research on bimaxillary expansion (BiMEx), combination of MMD and SARME, is reported sparsely. Main objective of this study is to provide three-dimensional evaluation of soft tissue effects following MMD and/or SARME. From 2008 to 2013, patients who underwent MMD and/or SARME were included. Stereophotogrammetry records were taken at time points: pre-operative (T1), direct post-distraction (T2) and 1-year post-operative (T3). Analyses were performed with automatic three-dimensional facial landmarking algorithm using two-dimensional Gabor wavelets. Twenty patients were included that all had undergone SARME. Twelve patients had undergone BiMEx. Age at time of surgery ranged from 16-47 years. There was a significant downward displacement of soft tissue pogonion. Furthermore, there was a significant mean increase of 2.20 mm for inter alar width and a non-significant mean increase of 1.77 mm for inter alar curvature point width. In conclusion, automatic stereophotogrammetry landmarking analysis of soft tissue effects showed downward displacement of soft tissue pogonion following BiMEx and transversal widening of inter alar width and a tendency for an increase of inter alar curvature point width after SARME.

INTRODUCTION

Transverse mandibular and maxillary deficiencies manifest in anterior and posterior crowding and/or in uni- or bilateral crossbite. Historically, these discrepancies were treated with orthodontic and/or dental extraction therapy. Since distraction was introduced for the facial skeleton in the early 90s of last century, new treatment options became possible[1,2].

Mandibular midline distraction (MMD) is an effective technique to widen the mandible in order to solve transverse mandibular deficiencies[2-4]. For transverse maxillary deficiencies, surgically assisted rapid maxillary expansion (SARME) is an accepted technique and well reported in the literature[5-9]. In some specific cases a combination of MMD and SARME is indicated, what is named as bimaxillary expansion (BiMEx)[10,11]. Research on MMD is mostly performed using conventional research methods including dental cast models and posterior-anterior cephalograms[4], whereas for SARME outcome of studies using three-dimensional (3D) imaging analysis techniques is available[9]. However, research on BiMEx is reported sparsely in the literature up to now[12,13], and to the authors' knowledge only one paper reports soft tissue effects following BiMEx using of 3D imaging analysis techniques[11].

Since 3D imaging techniques make it possible to analyse bony and overlying soft tissue structures more accurately compared with conventional two-dimensional (2D) radiographs, it is possible to obtain highly realistic skeletal and facial information. In addition, it is possible to acquire volumetric changes of bony and overlying soft tissue structures using 3D landmarking. This makes it possible to calculate a prediction of facial changes following MMD and/or SARME.

Soft tissue effects could be evaluated by 3D facial surface scans or stereo photographs, and are obtained using stereophotogrammetry. The resulting data is a cloud of triangulated 3D points that forms a 3D model on which a full colour texture of the face can be mapped. 3D surface scans have been used in landmark-based clinical research[14,15] with manually placed 3D landmarks. Recently, at the Erasmus MC, University Medical Center Rotterdam, the Netherlands a new method was created that can automatically place landmarks on facial surface data[16,17].

The main objective of this study is to provide a 3D evaluation of the soft tissue effects following MMD and/or SARME. These potential soft tissue effects could be taken into account by clinicians during the orthognathic surgery planning and could be used to inform patients.

MATERIALS AND METHODS

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

Patients

From 2008 to 2013, patients who underwent MMD and/or SARME at the Department of Oral and Maxillofacial Surgery, Erasmus MC, University Medical Center Rotterdam, the Netherlands, were included in this study.

The inclusion criteria were mandibular discrepancy (mandibular anterior and/or posterior crowding, uni- or bilateral crossbite) treated with MMD, and maxillary discrepancy (maxillary anterior and/or posterior crowding and/or uni- or bilateral crossbite) treated with SARME. Patients were at least 16 years old.

The exclusion criteria were congenital (craniofacial) deformity patients, additional orthognathic surgery following MMD (bilateral sagittal split osteotomy) and SARME (Le Fort 1) before 1 year post-operative, mental retardation, history of radiation therapy and head injuries leading to fractures and/or soft tissue scars in the facial area of interest, missing stereophotogrammetry record at T1 and/or T3 and insufficient stereophotogrammetry record quality by artefacts or obstructing hair in the facial area of interest.

For MMD, the surgical technique was similar to the described technique of Mommaerts et al[18] and only bone-borne distractors were used[10]. For SARME, the surgical technique applied was described by Koudstaal et al[7] and only tooth-borne distractors (Hyrax) were used. For MMD and SARME both, the surgical intervention was performed under general anaesthesia. At fixed time points, stereophotogrammetry records were taken: pre-operative (T1), direct post-distraction (T2) and 1-year post-operative (T3).

Stereophotogrammetry analysis

A 3D stereophotogrammetry setup with 4 cameras (EOS 1000D, CANON INC.) and an integrated software (DI3Dcapture, Dimensional Imaging, Version 6.8.16.4255) were used to capture 3D photographs of the face. All photographs were taken with natural head position and relaxed facial musculature.

The stereophotogrammetry analyses were performed with an automatic 3D facial landmarking algorithm combining template with shape based methods as described elsewhere[16,17]. In short, the automatic landmarking algorithm aligns the 3D surface scans, projects to 2D, and extracts 2D features that serve as input for multiple base 2D landmarking algorithms. These base algorithms are then combined using ensemble learning. After the landmarks are located, they are reverted back to 3D. Additionally, correlations between landmark coordinates in the training sample are used in a principal components (PCs) guided search. 26 landmarks were automatically placed. Additionally, all landmark positions were manually checked by three observers (AG, JPG and MAJ) and repositioned if necessary on the 3D (**Fig. 1**) and flat (**Fig. 2**) view.

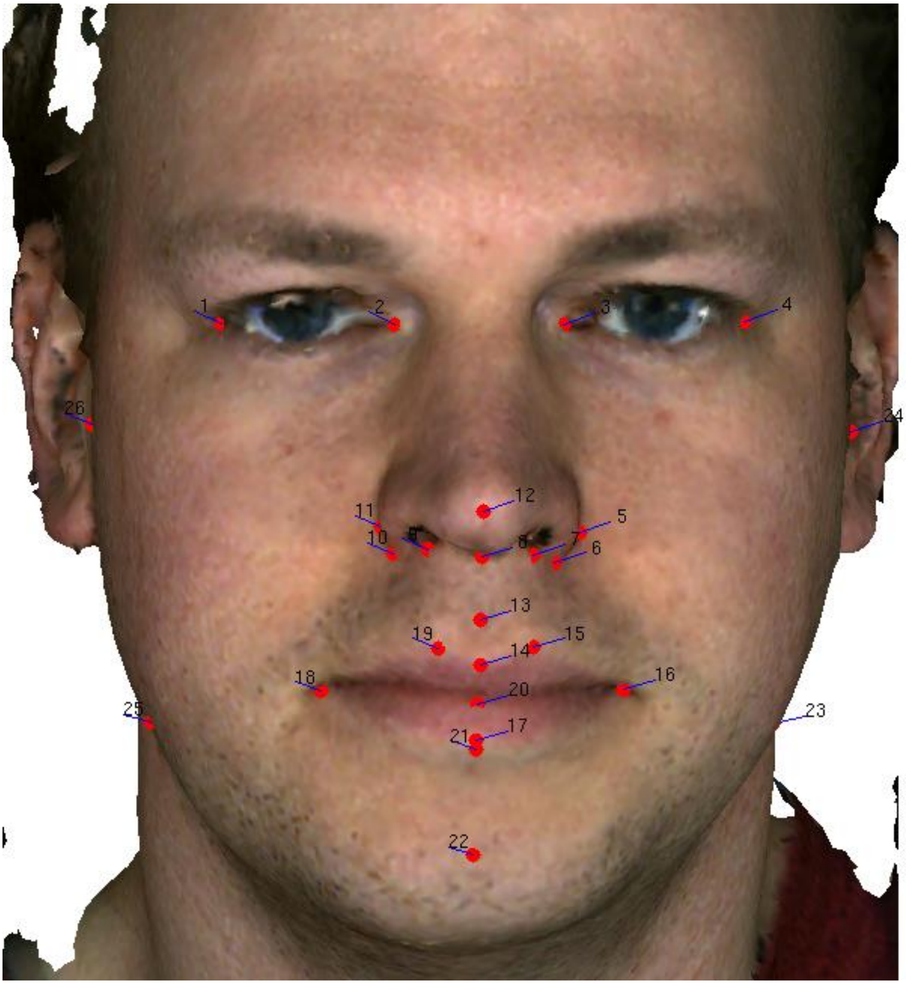

Fig. 1. Overview of 26 automatically placed facial landmarks on the 3D view.

The stereophotogrammetry analysis was divided in 2 regions. For MMD, these soft tissue regions were the condylion, gonion, pogonion, sublabiale, labiale inferius, cheilion and

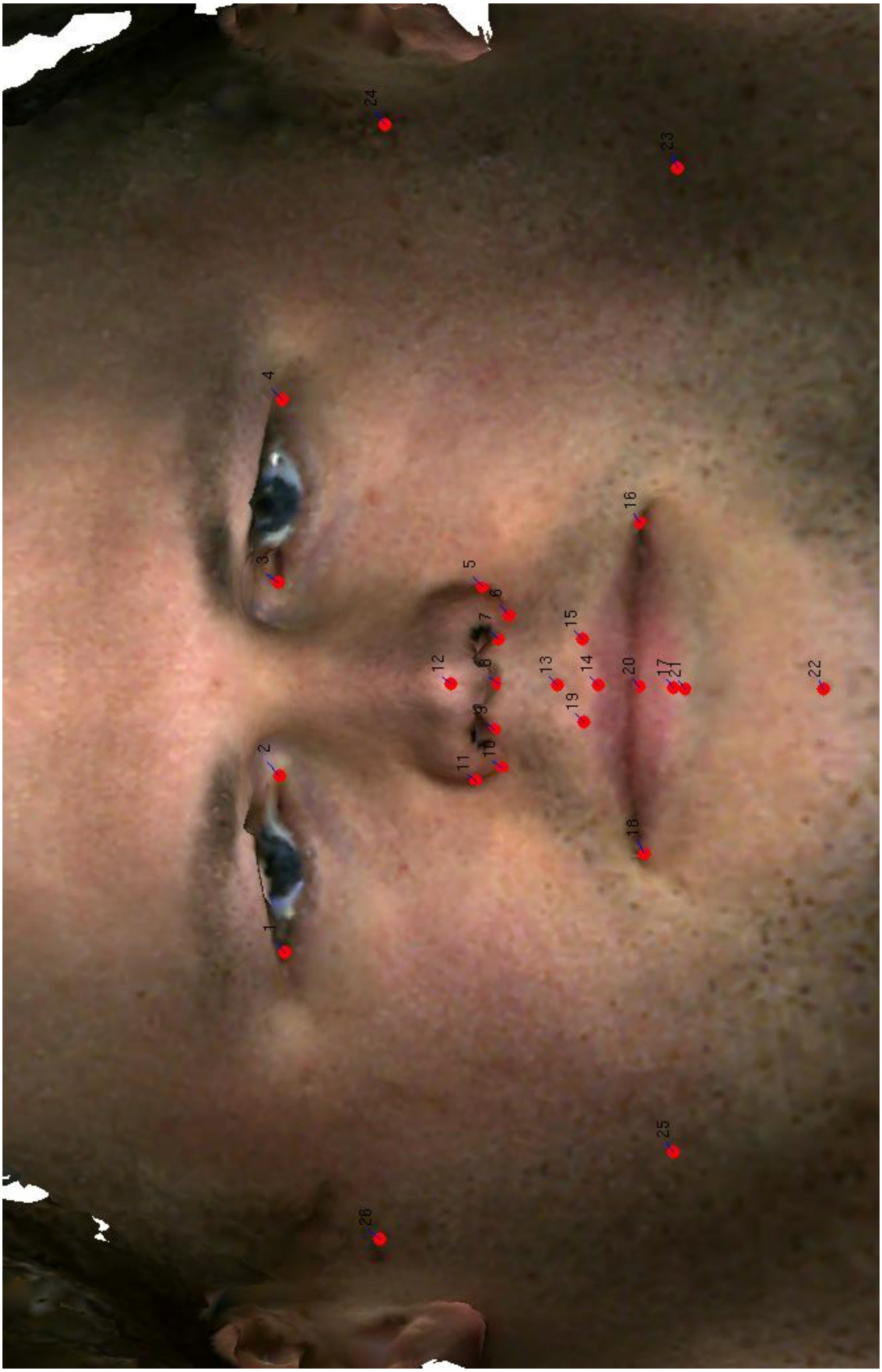

Fig. 2. Overview of 26 automatically placed facial landmarks on the flat view.

stomion. For SARME, these soft tissue regions were the pronasale, alare, alar curvature point, nostril base point, subnasale, subspinale, crista philtri and labiale superius

To assess the effect of MMD on the soft tissue structures, the following relevant point to point landmark distances were digitally measured: 25-23, 25-22, 23-22, 21-23, 21-25, 17-22, 17-21, 14-12, 22-1, 22-4, 18-16, 17-20, 17-16, 17-18, 26-24, 1-25 and 4-23.

For the effect of SARME on the soft tissue structures, the following relevant point to point landmark distances were digitally measured: 26-24, 11-5, 10-6, 9-7, 15-19, 16-18, 14-20, 8-12, 1-12, 4-12, 8-5, 8-10, 1-13, 4-13, 1-14, 4-14, 1-19 and 4-15.

The landmark distances between the left and right exocanthion (4-1), and left and right endocanthion (3-2) were used as a control measurement. See *Appendix I* for a list of the landmark's definition.

Table 1. Baseline patient characteristics.

T1-T3	BiMEx	SARME (without MMD)
Number of patients	12	8
Mean age (range)	29 (16-45)	31 (18-47)
Female:Male	8:4	5:3

Abbreviations: BiMEx, bimaxillary expansion; MMD, mandibular midline distraction; SARME, surgically assisted rapid maxillary expansion.

Because of incomplete records in T2, the stereophotogrammetry analysis was only performed for T1 and T3.

Statistical analysis

Two-sided paired samples T-tests were used to assess differences between T1 and T3. A Bonferroni correction (BC) was applied to adjust *P*-values for the MMD outcome (adjusted significance level $P < 0.0026$) and for the SARME outcome (adjusted significance level $P < 0.0025$), separately.

RESULTS

Patients

Twenty patients fulfilled the inclusion criteria. All of the 20 patients had undergone a SARME. Twelve of these patients had undergone a BiMEx.

The age at the time of surgery ranged from 16-47 years. See *Table 1* for the patient characteristics.

All the patients completed the treatment and the obtained transversal expansion for correcting the transversal discrepancy was obtained. Eleven out of the 20 patients underwent additional orthognathic surgery after 1 year follow-up. During MMD, only in 1 patient the bone-borne distractor caused a dehiscence in the buccal mucosa underneath the lower lip. This was transient and healed within 2 weeks by frequent flushing.

Table 2. Stereophotogrammetry analysis for MMD.

Landmark no.		T1 mean	T1 SD	T3 mean	T3 SD	diff	diff SD	*P*-value
1	4	90.23	3.30	90.75	3.70	0.52	1.52	0.264951
2	3	35.67	2.36	36.03	2.42	0.36	1.27	0.347393
25	23	110.71	11.63	114.44	13.78	3.73	7.50	0.112611
25	22	88.66	9.37	89.99	9.47	1.33	5.50	0.420623
23	22	89.79	11.	93.43	11.88	3.64	6.85	0.092566
21	23	90.80	10.27	94.08	11.73	3.28	6.78	0.122151
21	25	89.35	8.68	90.38	8.96	1.03	5.79	0.551859
17	22	34.18	5.54	35.12	4.69	0.95	5.05	0.529495
17	21	22.17	4.90	22.02	4.96	-0.15	3.62	0.890993
14	12	34.17	4.38	34.85	3.56	0.68	2.16	0.298288
22	1	119.17	8.20	122.36	7.54	3.19	2.44	0.000873*
22	4	119.29	7.93	122.41	7.35	3.11	2.56	0.001444*
18	16	49.28	3.10	50.44	3.80	1.16	3.17	0.231442
17	20	10.57	1.72	10.99	2.07	0.42	2.45	0.568333
17	16	30.61	2.52	30.38	2.30	-0.24	2.07	0.698722
17	18	30.39	2.22	30.13	3.51	-0.26	2.68	0.738356
26	24	138.36	11.32	139.28	11.17	0.92	2.82	0.284216
1	25	98.59	7.78	95.42	9.06	-3.17	6.48	0.118876
4	23	99.00	8.34	95.40	8.75	-3.60	6.51	0.081861

Abbreviations: diff, difference; MMD, mandibular midline distraction; SD, standard deviation.
Values are reported in millimeters.
* *P*-values significant after Bonferroni correction.
Note: The Bonferroni correction adjusts the *P*-value from 0.05 to 0.0026316.

Stereophotogrammetry analysis

In *Table 2*, the complete results of the stereophotogrammetry analysis are described for MMD. For the distance between landmark 22-1, there was a significant difference in the

Table 3. Stereophotogrammetry analysis for SARME.

Landmark no.		T1 mean	T1 SD	T3 mean	T3 SD	diff	diff SD	*P*-value
1	4	91.83	4.12	91.99	4.51	0.15	1.65	0.684464
2	3	36.61	3.16	37.04	3.30	0.43	1.40	0.185323
26	24	138.49	10.52	138.74	10.35	0.25	3.22	0.734357
11	5	34.93	2.99	37.13	3.32	2.20	1.76	0.000011*
10	6	24.82	2.13	26.59	2.92	1.77	2.63	0.003641
9	7	18.40	2.64	19.14	2.44	0.74	2.58	0.107022
15	19	13.43	2.41	13.46	2.15	0.02	1.87	0.953980
16	18	49.25	3.80	50.12	4.03	0.87	3.67	0.303071
14	20	8.34	1.73	8.40	2.59	0.06	2.00	0.890028
8	12	19.80	2.34	19.72	2.34	-0.08	2.84	0.897302
1	12	71.18	4.00	71.22	4.41	0.03	1.98	0.939200
4	12	71.47	4.26	71.18	4.38	-0.28	2.08	0.548059
8	5	22.70	1.53	23.56	2.71	0.86	2.72	0.174075
8	10	15.52	1.71	16.13	1.99	0.61	1.66	0.114247
1	13	73.43	4.27	73.47	4.20	0.04	1.39	0.906020
4	13	74.13	4.25	74.02	4.40	-0.11	2.17	0.824239
1	14	81.34	4.30	81.96	4.48	0.62	1.81	0.142973
4	14	82.00	4.20	82.53	4.26	0.54	1.76	0.187736
1	19	75.91	4.17	76.52	4.11	0.61	1.96	0.182647
4	15	76.54	4.04	77.11	4.06	0.56	1.74	0.165240

Abbreviations: diff, difference; SARME, surgically assisted rapid maxillary expansion; SD, standard deviation.
Values are reported in millimeters.
* *P*-values significant after Bonferroni correction.
Note: The Bonferroni correction adjusts the *P*-value from 0.05 to 0.0025.

scores for T1 (mean = 119.17, standard deviation (SD) = 8.20) and T3 (mean = 122.36, SD = 7.54), *P* = 0.000873. Even after applying BC, this significance still holds. For the distance between landmark 22-4, there was a significant difference in the scores for T1 (mean = 119.29, SD = 7.93) and T3 (mean = 122.41, SD = 7.35), *P* = 0.001444 (significant after BC). These outcomes indicate a downward displacement of the soft tissue pogonion.

Regarding the inter soft tissue gonion distance (25-23), there was an non-significant difference in the scores for T1 (mean = 110.71, SD = 11.63) and T3 (mean = 114.44, SD = 13.78), *P* = 0.112611. This outcome indicates a tendency for an increase of the inter soft tissue gonion distance, although not significant.

In *Table 3*, the complete results of the stereophotogrammetry analysis are described for SARME. For the distance between landmark 11-5, there was a significant difference in the scores for T1 (mean = 34.93, SD = 2.99) and T3 (mean = 37.13, SD = 3.32), *P* = 0.000011. Even after applying BC, this significance holds. This outcome indicates a transversal widening of the inter alar width. For the distance between landmark 10-6, there was a significant difference in the scores for T1 (mean = 24.82, SD = 2.13) and T3 (mean = 26.59, SD = 2.92), *P* = 0.003641. However, after applying BC this significance disappeared. This outcome indicates a tendency for an increase of the inter alar curvature point width.

DISCUSSION

In this retrospective observational study, we looked at 3D evaluation of the soft tissue effects following MMD and/or SARME. Stereophotogrammetry records at T1 and T3 were analysed with an automatic 3D facial landmarking algorithm using 2D Gabor wavelets as described by De Jong et al[16,17]. The results showed a downward displacement of the soft tissue pogonion with a tendency for an increase of the inter soft tissue gonion distance. Furthermore, a transversal widening of the inter alar width and a tendency for an increase of the inter alar curvature point width were observed.

Regarding MMD, these results are similar to what was described by Bianchi et al[11]. In their study, a forward and downward displacement of the chin was observed with a forward projection of the lower lip[11]. It should be noted that simultaneous SARME was performed in their study and in the present study. Regarding the downward displacement of the soft tissue pogonion in the present study, we think this is the effect of the maxillary downward displacement following SARME. This theory is strongly supported by Xi et al[19], as they observed a skeletal downward displacement of the maxilla with a clockwise rotation of the mandible and inferior chin displacement after only SARME[19]. Therefore, this should be interpreted as a result of BiMEx instead of the MMD in the present study.

Furthermore, there was no significant displacement observed of the lower lip region in the present study. It must be noted that differences in lip projection could be created by dental movements due orthodontic treatment, which is not a solitary effect of MMD. This makes comparison and analysis difficult.

There was a tendency for increase of the inter soft tissue gonion distance when looking to the soft tissue structures in this region. This outcome is in concordance with De Gijt et al[4], as they observed a slight increase of the skeletal ramal angle (RA) at T3. In their study, a bone-borne distractor was applied as well and this increase was not significant with no difference of the skeletal RA in the long-term (6.5 years) follow-up[4]. However, this outcome could be strongly related to the type of distractor. Tooth-borne distractors practice their force on dentoalveolar level and theoretically would create more posterolateral widening compared to bone-borne distractors, which practice their force anteriorly on basal bone level only. Related to this, in the gonion region the soft tissue effects might be different dependent on the type of distractor. To our knowledge, no study has been conducted to compare the soft tissue effects of both distractor types following MMD.

Regarding SARME, similar soft tissue effects were observed by Nada et al[20]. In their study, an increase in the nasal volume and inter alar width was observed at 22 months post-SARME[20]. This outcome is an aesthetic effect of SARME for clinicians, which has to be taken into account when planning the orthognathic surgery. In the present study, there was a mean increase of 2.20 mm for the inter alar width and a mean increase of 1.77 mm for the inter alar curvature point width. Although these increases are minimal, it is difficult to predict how the patients will experience these soft tissue effects from aesthetic aspects.

In the present study, a limitation is that the sample size of our study was around *n*=30 per group or smaller which might lead to bias in *P*-values of the two-sided paired samples T-test. However, we have also compared groups with the non-parametric two-sided Wilcoxon Sign-Rank test but found the same significant differences. A second limitation is that the T2 stereophotogrammetry records were not complete for all the included patients. This made it impossible to analyse the soft tissue effects of MMD and/or SARME during the treatment at end of distraction. Since aesthetic aspects are getting more importance in the orthognathic surgery, it is essential to provide the patients a prediction of the soft tissue effects during the treatment as well. There was a downward displacement of the soft tissue pogonion after BiMEx. However, this outcome does not provide a prediction of soft tissue effects for patients who will undergo MMD without simultaneous SARME. BiMEx seems to be beneficial for patients with a short lower third part of the face. On the other hand, BiMEx could lead to undesirable soft tissue effects for patients with a pre-existing gummy smile and long face. The transversal widening of the inter alar width after SARME could be undesirable as well for patients. Clinicians should communicate these possible soft tissue effects with the patients carefully during the planning of the orthognathic surgery. The soft tissue effects of MMD without simultaneous SARME are not clarified yet. There is still a lack of knowledge about the difference between the soft tissue effects of the different types of distractors following MMD.

In conclusion, automatic stereophotogrammetry landmarking analysis of soft tissue effects showed a downward displacement of the soft tissue pogonion following BiMEx and a transversal widening of the inter alar width and a tendency for an increase of the inter alar curvature point width after SARME. Clinicians should communicate these possible soft tissue effects with the patients carefully during the planning of the orthognathic surgery.

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Appendix I. Landmark's definition.

Landmark no.	Definition
1.	Exocanthion, right.
2.	Endocanthion, right.
3.	Endocanthion, left.
4.	Exocanthion, left.
5.	Alare, left.
6.	Alar curvature point, left.
7.	Nostril base point, left.
8.	Subnasale.
9.	Nostril base point, right.
10.	Alar curvature point, right.
11.	Alare, right.
12.	Pronasale.
13.	Subspinale.
14.	Labiale superius.
15.	Crista philtri, left.
16.	Cheilion, left.
17.	Labiale inferius.
18.	Cheilion, right.
19.	Crista philtri, right.
20.	Stomion.
21.	Sublabiale.
22.	Soft tissue pogonion.
23.	Soft tissue gonion, left.
24.	Soft tissue condylion, left.
25.	Soft tissue gonion, right.
26.	Soft tissue condylion, right.

PROSPECTIVE CLINICAL STUDIES

6

Long-term (6.5 years) follow-up of mandibular midline distraction

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ABSTRACT

To assess the long-term stability and biomechanical effects of mandibular midline distraction (MMD), a prospective observational study was conducted with a retrospective cohort. Included were 17 MMD patients, of whom 9 completed the long-term follow-up with a mean of 6.5 years. In all patients a bone-borne distractor was used. Dental casts and posterior-anterior (PA) cephalograms were taken at fixed time points: pre-operative (T1), directly post-distraction (T2), 1-year post-operative (T3) and long-term follow-up (T4). Inter canine (ICD), inter first premolar (IPMD), inter first molar (IMD) distances and arch perimeter (AP) were measured on dental casts. From the PA cephalograms intercondyle distance (ID) and the ramal angle (RA) were obtained. A significant and sustained widening was observed in most measurements. The greatest overall transverse expansion (T1-T4) occurred in the IPMD (4.1 ± 0.76 mm, $P < 0.05$), the ICD, IMD and AP increased respectively: 2.0 ± 0.72mm, 3.8 ± 0.82mm and 3.5 ± 0.82mm. The ID did not change significant ($P > 0.05$) during all phases of the study. An increase of RA was observed initially, however, no difference was noted on the long-term. This study showed that MMD is a stable method to expand the mandible, with no skeletal effect on the temporomandibular joint.

INTRODUCTION

Transverse mandibular discrepancies manifest in anterior and posterior crowding and uni- or bilateral crossbite. This can be prominent in patients with congenital deformities such as Treacher-Collins syndrome, Apert syndrome, Crouzon syndrome, Nager syndrome. However, it can be present in non-syndromal patients as well. Traditionally, transverse discrepancies are treated with orthodontic appliances and/or teeth extractions. The intermaxillary suture can be expanded using orthodontic appliances until around 15 years[1]. The mandibular symphysis however, closes at the age of 1, therefore expanding the mandible without surgical intervention is impossible[2,3].

In the early 90s of last century distraction techniques were introduced for the facial skeleton and new treatment options became available[4-6]. Mandibular midline distraction (MMD) is the technique where the mandible is widened using distraction. An osteotomy is performed and a distractor is attached on both sides of the osteotomy, following the activation of the distractor both histio- and osteogenesis occur.

Solitary MMD can be indicated when the transversal discrepancy only affects the mandible. However, transversal discrepancies often affect both the maxilla and the mandible, and bimaxillary expansion (BiMEx) is indicated to maintain proper occlusion. The distractor itself can be attached to the bone, the teeth or a combination of both. Biomechanical aspects of distractors are important as they influence the outcome of distraction in the long-term, specifically relapse[7]. Though short-term series on MMD have been reported, long-term clinical studies are lacking on the biomechanical effects of bone-borne distractors in MMD. The primary objective of this study is to evaluate the long-term biomechanical effects of MMD on dental and skeletal level.

MATERIAL AND METHODS

A prospective observational study with a retrospective cohort was performed at the Erasmus MC, University Medical Center Rotterdam, the Netherlands. The patient cohort was derived from patients included in a prospective study on surgically assisted rapid maxillary expansion (SARME) who also underwent MMD in one operation, BiMEx[8]. Approval of the Standing Committee on Ethical Research in Humans of the Erasmus MC, University Medical Center Rotterdam, the Netherlands was obtained (MEC 2011-265). All patients were re-invited to our clinic for the long-term follow-up. All participating patients underwent BiMEx surgery before 2008. The surgical technique was similar to what Mommaerts et al. described and two different bone-borne distractor device were used, namely: TMD-flex and the Rotterdam Mandibular Distractor[9,10]. During this study, dental casts and posterior-anterior (PA) cephalograms were obtained at fixed time points: pre-operative (T1), direct post-distraction (T2), 1-year post-operative (T3) and the long-term follow-up (T4).

Inclusion criteria for this study were:
- Mandibular discrepancy (mandibular anterior and/or posterior crowding, uni- or bilateral crossbite)
- Age 18 years or above
- Treated before 2008

Exclusion criteria were congenital craniofacial deformity patients, a history of radiation therapy in the area of interest and mental retardation.

Dental cast study

On the mandibular dental cast the following distances were measured; inter canine (ICD), inter first pre-molar (IPMD) and inter first molar (IMD), further the arch perimeter (AP) was obtained using the method described by Chung et al.[11]. For ICD, IPMD and IMD the tip of the (disto-)buccal cusps were used (**Fig. 1**). The AP was defined as the sum of the left and right distance from the mesial anatomic contact points of the mandibular first permanent molars to the contact point of the central incisors or to the midpoint between the central incisor contacts, if spaced during distraction (**Fig. 1**).

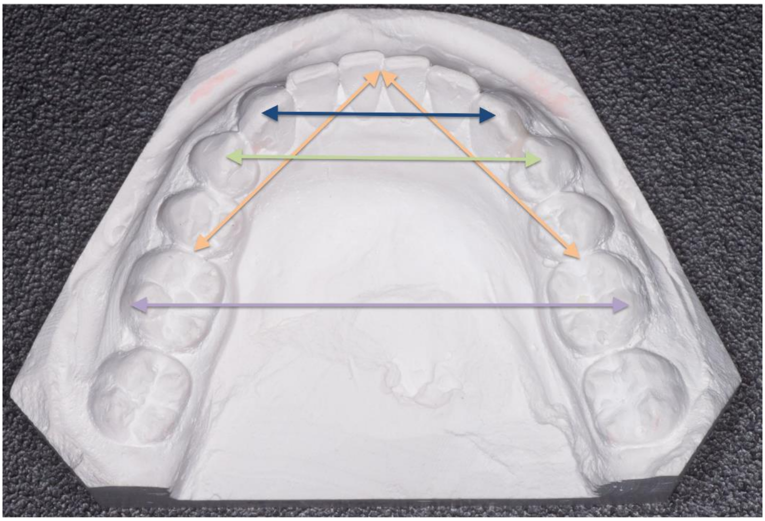

Fig. 1. Dental cast analysis.
Blue line: ICD; green line: IPMD; purple line: IMD; orange line: AL.

All measurements were performed using an electronic digital caliper (Kraftixx®, art.0906-90) with an accuracy of 0.02 mm on the dental cast study models.

Posterior-anterior cephalograms analysis

Cephalometric analyses were performed on PA cephalograms, see **Fig. 2**. To assess the effect of MMD on the mandible the ramal angle (RA) and the intercondyle distance (ID) were measured[12].

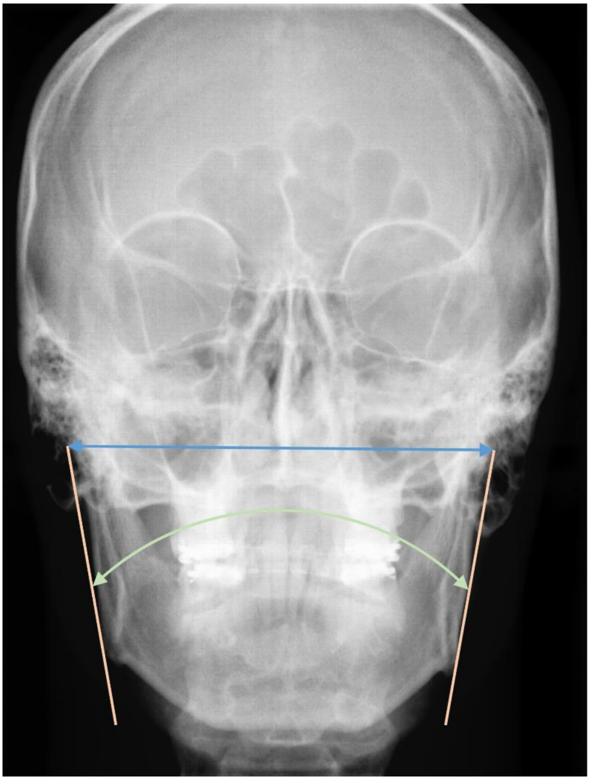

Fig. 2. PA-cephalogram analysis.
Blue line: ID; green line: RA; orange lines: line from lateral part of the condyle and gonion.

The landmarks used in this analysis were: the most lateral part of left and right condyle head (Lco and Rco); left and right gonion (Lgo and Rgo). ID was obtained by measuring the distance between Rco and Lco. By creating a line from the lateral condyle to gonion and measure the angle between the left and right side RA was acquired (Lco-Lgo/Rco-Rgo). The distance between the left and right zygomatic process (Lzp and Rzp) was used as a control measurement. All measurements were digitally performed with iSite Enterprise (Phillips Healthcare Informatics, Foster City, California, United States of America).

Statistical analysis

The statistical analysis was performed in collaboration with the department of Biostatistics of the Erasmus MC, University Medical Center Rotterdam, the Netherlands. The analyses were performed using the Statistical Package of the Social Sciences (version 20.0, SPSS Inc, IBM Corporation). All measurements were performed twice by the author and the mean value was used for the analysis.

The longitudinal changes were evaluated using Mixed Models ANOVA, with a Bonferroni correction. Because of the fact that during the follow-up period, other surgeries might be performed, bilateral sagittal split osteotomy and teeth extractions were added as fixed factors in respectively the PA cephalogram analysis and the dental cast analysis. A P-value of < 0.05 was considered significant.

Reliability analysis

To assess inter- and intra-observer agreement an intraclass correlation coefficient (ICC) was obtained. Therefore, for the inter-observer reliability all measurements were also done by the second author. An ICC value of ≥ 0.9 was considered reliable.

RESULTS

In this study 17 MMD patients were included. The age at the moment of surgery ranged from 13 to 43 years and all patients underwent SARME. For the long-term follow-up 9 patients returned to our department. See *Table 1* for the baseline characteristics of all the patients.

Table 1. Baseline patient characteristics.

	T1-T3	T4
Number of patients	17	9
Mean age	26 (range: 13-43)	28 (range: 13-43)
Male:Female	9:8	3:6

Dental cast study

In *Table 2* and *4* and **Fig. 3-6** the complete results of the dental cast study measurements are listed. All measurements were significantly influenced by time ($P < 0.05$). Compared to the pre-operative time point (T1) all transverse measurements showed an increase. Regarding the first year follow-up all transverse distances were significant expanded by MMD ($P < 0.05$). The greatest expansion (T1-T2) was seen in the IPMD region: 4.9 mm (P <

0.05), ICD and IMD increased respectively 4.9 and 2.4 mm (P < 0.05). After the first year of treatment (T3-T2) the ICD decreased 1.5 mm (P > 0.05), all other measurements slightly increased (P > 0.05).

Table 2. Dental cast study.

	T1		T2		T3		T4		Time
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	P-value
ICD	20.0	1.11	24.4	1.33	22.9	1.09	22.0	1.03	0.03*
IPMD	26.5	1.10	31.4	1.13	31.7	1.03	30.6	0.88	< 0.001*
IMD	42.3	0.99	44.8	1.01	45.2	0.94	46.1	1.26	< 0.001*
AL	53.6	2.32	58.1	2.66	58.7	2.18	57.1	1.98	< 0.001*
Follow-up (months)	-2		2		13		78		

Distances in mm: ICD: intercanine distance, IPMD: interpremolar distance, IMD: intermolar distance, AL: arch length. S.E.: standard error, * = P < 0,05.

Table 3. Posterior-anterior cephalometry.

	T1		T2		T3		T4		Time
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	P-value
ID	122.1	1.88	121.0	2.02	121.6	1.97	122.0	1.88	0.17
RA	24.0°	1.34	26.9°	1.35	25.2°	1.36	24.0°	1.43	0.002*
ZZ	135.4	1.88	135.1	1.71	135.5	1.66	135.8	1.53	0.52

Distances in mm: ID: intercondyle distance, ZZ: interzygoma distance. Angle: RA: ramal angle. S.E.: standard error, * = P < 0,05.

Concerning the long-term follow-up (T1-T4) all measurements showed a significant increase (P > 0.05), only the ICD was not significantly increased (P < 0.05). No significant relapse was found between T3-T4 in all measurements (P > 0.05).

The arch perimeter increased after distraction and orthodontic aligning, however during the long-term follow-up, T3-T4, relapse occurred though not significant (-1.6 mm, P > 0.05).

Posterior-anterior cephalogram analysis

In *Table 3* and *4* and **Fig. 7** and **8** the results of the PA cephalogram measurements are listed. The ID did not change significantly (P > 0.05) at any of the time phases. The cephalometric analyse showed a significant (P < 0.05) increase of the ramal angle between T1-T2. However, the medium (T3) and long-term follow-up (T4) showed no significant difference with the initial ramal angle (T1). The inter zygomatic process distance did

Table 4. Longitudinal results.

	T1-T2			T1-T3			T1-T4			T4-T3			T3-T2		
	Mean	S.E.	P-value	Mean	S.E.	P-value	Mean	S.E.	P-value	Mean	S.E.	P-value	Mean	S.E.	P-value
ICD	4.4	0.60	<0.001*	2.9	0.52	<0.001*	2.0	0.72	0.20	-0.9	0.59	1.00	-1.5	0.62	0.16
IPMD	4.9	0.76	<0.001*	5.2	0.69	<0.001*	4.1	0.76	<0.001*	-1.0	0.70	0.96	0.3	0.72	1.00
IMD	2.4	0.42	<0.001*	2.9	0.46	<0.001*	3.8	0.82	0.002*	0.9	0.43	0.32	0.4	0.30	1.00
AL	4.6	1.03	0.002*	5.1	1.11	0.001*	3.5	0.35	0.35	-1.6	0.81	0.81	0.6	1.10	1.00
ID	-0.4	0.77	0.94	-0.6	0.79	1.00	-0.1	1.08	1.00	0.5	1.06	1.00	0.6	0.81	1.00
RA	-1.1°	0.67	0.001*	1.2°	0.72	0.67	0.0°	1.09	1.00	-1.2°	1.05	1.00	-1.7°	0.72	0.15

Distances in mm: ICD: intercanine distance, IPMD: interpremolar distance, IMD: intermolar distance, AL: arch length, ID: intercondyle distance. Angle: RA: ramal angle. S.E.: standard error, * = P < 0,05.

not change between the PA cephalograms over all the time phases indicating a reliable measurement.

Reliability analysis

The ICC for each separate measurement, both inter- and intra-observer, were ≥0.9 indicating that the measurements were reliable.

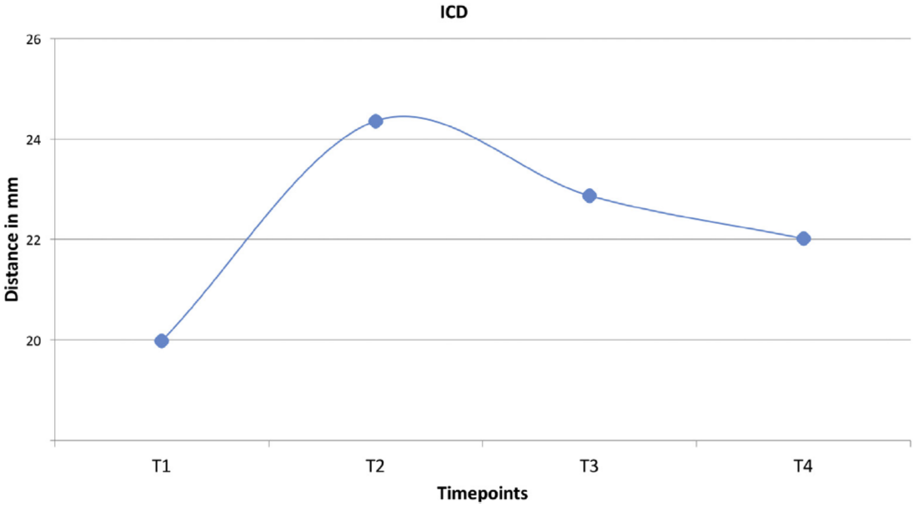

Fig. 3. Inter canine distance (ICD).

Fig. 3. Inter canine distance (ICD).

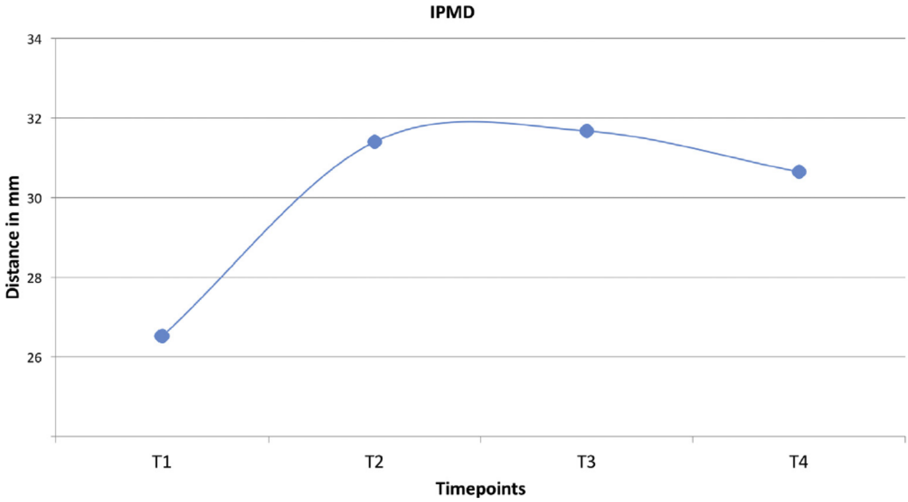

Fig. 4. Inter premolar distance (IPMD).

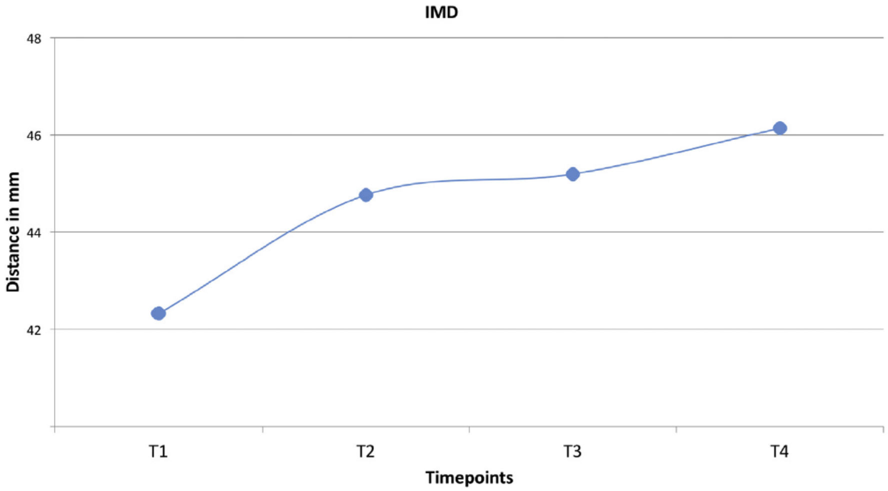

Fig. 5. Inter molar distance (IMD).

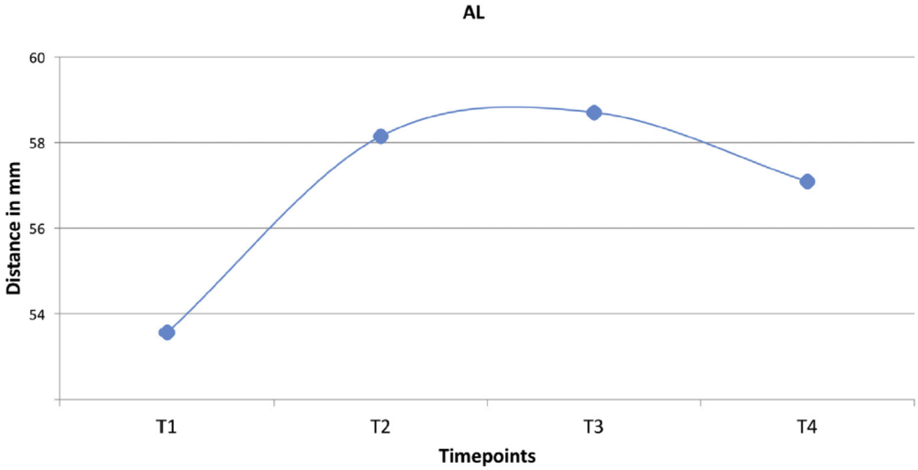

Fig. 6. Arch length (AL).

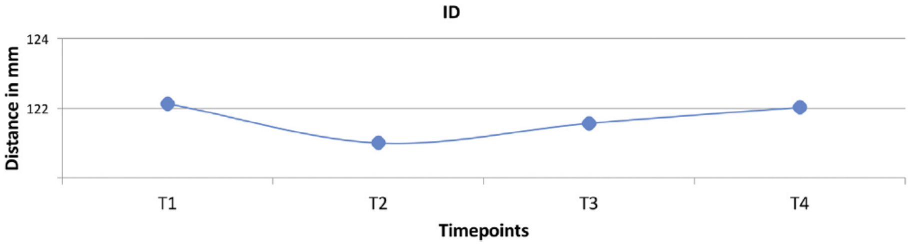

Fig. 7. Intercondyle distance (ID).

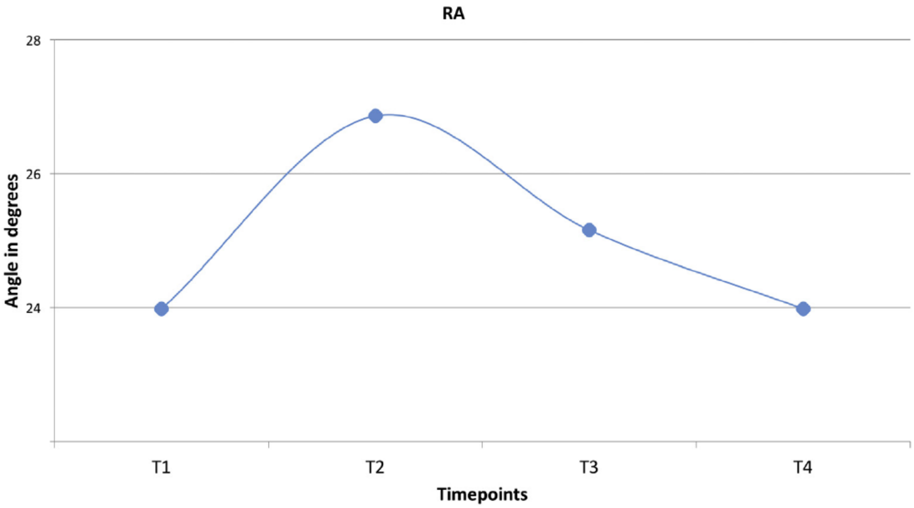

Fig. 8. Ramal angle (RA).

DISCUSSION

With the introduction of MMD a surgical procedure to widen the mandible became available to overcome large transverse mandibular discrepancies without having to extract healthy teeth[6]. The aim of this study is to assess the stability and relapse of MMD on the long-term.

Different studies with stable results have been published since the introduction[11-15]. Since the procedure is relatively new, the follow-up period of these studies was limited to a period of 1 to 3 years post-surgery. At this time, in most cases, orthodontic treatment has just finished and the stability of the surgical procedure itself is not proven by these studies. Therefore, longer follow-up periods are necessary to address stability of the procedure. Only King et al. conducted a study with a follow-up time of more than 3 years.

In literature, relative consensus is available concerning the surgical technique and distraction pattern. However, there is no consensus regarding the use of a particular distractor device. Three types of distractors are known namely, bone-borne, tooth-borne and hybrid. The main difference between the appliances is the position on which the distractors are fixed; the bone-borne devices are fixed to the bone, the tooth-borne to teeth and the hybrid to both. As a result of the different fixation positions different biomechanical effects can be expected. In theory, the benefit of a bone-borne distractor and to a lesser extend the hybrid-distractor, is the appliance of the distractor forces at basal bone level[16]. A more parallel expansion of the hemi-mandibles is expected. A more coronal application of the vector, in the case of a tooth-borne device, can cause angulation between the hemi-mandibles and thus a less parallel distraction gap. This might result in a less stable result of the expansion. Furthermore, the rigidity of the distractor appliances differs and this might influence the direction of the applied forces[9,10]. In this study both rigid and less rigid bone-borne distractors were used. To our knowledge, the study we present has the longest follow-up of MMD patients using a bone-borne distractor, with a relatively large sample.

The results show that after the initial distraction (T1-T2) a significant increase in width is achieved in all dental cast measurements. Initially the greatest increase can be found in the pre-molar and canine region. Following orthodontic treatment a decrease of ICD is observed. This decrease in distance is the result of the orthodontic treatment moving the canines medially in the direction of the distraction gap. At premolar and molar level teeth this effect is smaller resulting in a smaller decrease of width. For the 1-year follow-up (T3) these results are similar to what is previously described in literature[11-14]. On the long-term no significant relapse was found in the dental cast analysis between T3 and T4 indicating a stable result. In literature, only King et al. conducted a long-term follow-up study to assess the stability of MMD with the use of hybrid distractor[13]. The results of the King et al. study indicate a stable long-term result after treatment. Because of the different time-points used in their study it is difficult to directly compare the results of this study with the study of King et al. Although similar results are presented in their study, it appears that, especially in the premolar region more relapse is observed than in our patient group in the post-distraction and post-treatment phase. This indicates that more tooth movement was needed during the treatment. It was not explained if this was due to the fact that pre-distraction expansion was obtained by orthodontic forces and thus more dentoalveolar expansion. It is important to limit dentoalveolar expansion as it would increase the risk of fenestration and periodontal problems[17].

Concerning the arch length a significant increase between T1 and T3 of 5.1 mm was achieved which remained stable until T4. Although the arch length decreased during T3-T4 this was not significant. Compared to King et al. more arch length was gained ($T_{\text{pre-op}}$-$T_{\text{long-term}}$: 1.5 mm $P > 0.05$, this study: 3.6 mm $P > 0.05$)[13]. This might indicate a more anterior width increase with the use of a bone-borne device.

A cephalometric analysis was performed to analyse the effect of MMD on the temporomandibular joint. Only minor and non-significant differences were found in ID. King et al. have shown non-significant changes in ID[13]. Noticeably, between the pre-distraction and post-distraction time points a more lateral movement of the condyle is reported. This is in concordance with the fine element study of Kim et al. which states that with the use of a hybrid distractor, the distraction forces are located more cranially and distally, similar to a tooth borne device[18]. Therefore, the condyles are pushed further lateral in hybrid and tooth-borne devices than bone-borne devices. This could create a bigger force in the region of masticatory muscles and the temporomandibular joints. However, in this study, initially, the ramal angle did increase during the distraction phase nevertheless the ramus and condyle adapted to the new situation and the ramal angle rapidly decreased after the distraction phase. Since this study only used PA-cephalograms, new imaging techniques would give more insight on the effect of MMD on the temporomandibular joint. To our knowledge, in literature no reports of severe temporomandibular joint symptoms after MMD are reported. Further research would objectify the effects of the different distractors on the temporomandibular joint.

Although the choice of the distractor might be influenced by the biomechanical aspects, other aspects must be taken in account. The patients' experience of the distractor can differ as a result of the different positions of the distractor. A tooth-borne distractor is positioned lingual of the dental arch close to the tongue and this might be uncomfortable for the patient as it can interfere with tongue function (speech, swallowing et cetera.). The buccal position of the hybrid and bone-borne devices might harm the buccal mucosa, is more prone to wound dehiscence and can be a visible and painful volume underneath the lip. Tooth-borne and hybrid devices are always custom-made and therefore more expensive. However, the need for a second procedure to remove the hybrid or bone-borne distractor is both an extra physical and financial burden for the patient and the health care system. To resolve the scientific debate on the use of a specific distractor type, a randomized controlled trial should be performed.

Major advantages of this study are the long-term follow-up period, a large patient cohort and the nature of this prospectively followed group. As result of the long follow-up period, the use of cone-beam computer tomography (CBCT) or conventional multi-slice computer tomography (MSCT) were not implemented during the initial research design. Such a design would give even more insight in the biomechanical aspect of MMD. For future research the incorporation of these new image modalities would be advisable.

CONCLUSION

This study presents the long-term follow-up of a patient cohort treated with MMD using a bone-borne distractor device. The results show a stable dental result after 6.5 years, showing it to be a reliable treatment option for transverse discrepancies. Furthermore, this study shows that bone-borne devices have no positional effect on the temporomandibular joint indicating minimal risk of craniomandibular dysfunction following MMD. The choice of the distractor depends on more factors, including surgeons' and orthodontists' preference and patient friendliness. More research is necessary with state-of-the-art imaging techniques such as CBCT and a randomized controlled trial design.

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7

Follow-up of surgically assisted rapid maxillary expansion after 6.5 years: Skeletal and dental effects

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ABSTRACT

Surgically assisted rapid maxillary expansion (SARME) is a surgical technique to widen the maxilla. This study presents the long-term (6.5 years) follow-up results of SARME. A prospectively followed cohort of SARME patients were invited for a long-term follow-up. Dental casts and posterior-anterior cephalograms were taken. On the dental casts the following measurements were made: transversal distances at canine, premolar and molar level, arch length, palatal width and depth at premolar and molar level. On posterior-anterior cephalograms the distance between the left and right nasal base and the widening of inferior maxilla were measured. 17 patients were included for the long-term follow-up. Bone- and tooth-borne distractors were used in respectively 8 and 9 patients. In the dental cast study, a significant increase in transversal width was obtained in the canine, premolar and molar region and this remained stable in the long-term. The arch length did not significant increase in the long-term. The palatal width significantly increased, in the premolar and molar region. No effect was seen in palatal depth. On the posterior-anterior cephalograms an increase in the width of the inferior part of the maxilla was observed although this increase was not significant in the long-term. No significant changes of the nasal base was observed. In the long-term, SARME is a predictable method to widen the maxilla.

INTRODUCTION

Surgically assisted rapid maxillary expansion (SARME) is a surgical technique used for widening the maxilla. Indications for SARME include transverse discrepancies, which can present in both syndromal as well as in non-syndromal patients. Clinically, transversal discrepancies manifest in an uni- or bilateral crossbite, buccal corridors, anterior crowding, buccal tipping of the maxillary molars and lingual tipping of the mandibular molars. Congenital deformities that may affect the maxillary width include: cleft , Fronto-nasal dysplasia, Apert’s syndrome, Pfeiffer’s syndrome and Saethre-Chotzen syndrome[1].

Succesful skeletal maxillary expansion can be achieved with conventional orthodontic rapid maxillary expansion. After the age of approximately 15 years surgical intervention may be necessary to succesfully expand the maxilla. It has been suggested that the heavy interdigitation of the midpalatal and circummaxillary sutures may be the reasons for resistance to separation[2-4]. Recently, successful expansion using bone anchors have been reported[5]. Different surgical procedures have been described and at least a bilateral corticotomy is performed. In addition a midline osteotomy can be performed, concerning the position of this osteotomy different techniques are described. Further, in literature there are supporters and opponents of releasing the pterygoid plates[6].

After the osteotomies have been performed the expansion is initiated using a distractor. Roughly, two different distractor types are available. Bone-borne distractors, which are applied to the maxillary bone and tooth-borne distractors, which are fixed to two or more teeth on each side of the maxilla. In a prospective randomized controlled trial no significant differences between both distractors were observed[7]. Since little is known about the effects of SARME in the long-term this study was performed focussing on dental and skeletal tissue.

MATERIAL AND METHODS

An observational study was conducted at the Erasmus MC, University Medical Center Rotterdam, the Netherlands. The patient cohort was derived from the prospective study on SARME performed by Koudstaal et al.[7]. After approval of the Standing Committee on Ethical Research in Humans of the Erasmus MC, University Medical Center Rotterdam, the Netherlands in 2011 (MEC 2011-265) all patients were re-invited by mail to our clinic for a long-term follow-up. All participating patients underwent surgery before 2008. During the initial study, dental casts and posterior-anterior cephalograms were obtained at fixed time points, namely: pre-operative (T1), direct post-operative (T2), 1-year post-operative (T3). Only patients who responded for the long-term follow-up were included in this study. Dental cast and a posterior-anterior cephalogram were obtained for the long-term follow-up (T4).

Surgical technique

The surgical procedure was the same for both bone- and tooth-borne distractor. Using a Le Fort I approach, buccal osteotomies were meade sectioning the lateral nasal well as well. A median osteotomy was performed between the central incisors and an osteotome was used to mobilize the segments. At the end of the surgery the distractor was tested and the oral mucosa sutured. When a tooth-borne distractor was used it was pre-operatively inserted by the orthodontist. If a bone-borne distractor was used, it was inserted during surgery. For the specific type of distractor used during the study see Koudstaal et al.[7].

Dental cast study

On the dental cast the following transversal distances were measured: inter canine (ICD), inter first pre-molar (IPMD) and inter first molar (IMD). The arch perimeter (AP), palatal depth and width were also obtained. The palatal depth and width are measured at the first premolar and first molar level. Since the distractor was in place at T2 no measurements were made at this timepoint. For ICD, IPMD and IMD the tip of the (disto-)buccal cusps were used (**Fig. 1**)[7]. To measure the AP the distances between the contact points on the mesial surface of the first molar, the mesial surface of the first premolar, and the distal surface of the central incisor on both sides were added together[8]. To assess palatal width and depth the technique described by Northway et al. was used[9]. All measurements on the dental casts were made with an electronic digital caliper with an accuracy of 0.02 mm (Kraftixx®, art.0906-90).

Posterior-anterior cephalograms analysis

To evaluate the skeletal response when the maxilla was expanded cephalometric analyses were performed on PA cephalograms. To assess widening of the nasal floor the distance between the lowest point of the left and right piriform appertura were measured (NN). To assess widening of the inferior part of the maxilla, the distance between intersection of the molar and the alveolar process on the left and right were measured (MM). The distance between the left and right zygomatic process (ZZ) were used as a control measurement. All measurements were digitally performed with sidexis (Phillips, Eindhoven, the Netherlands).

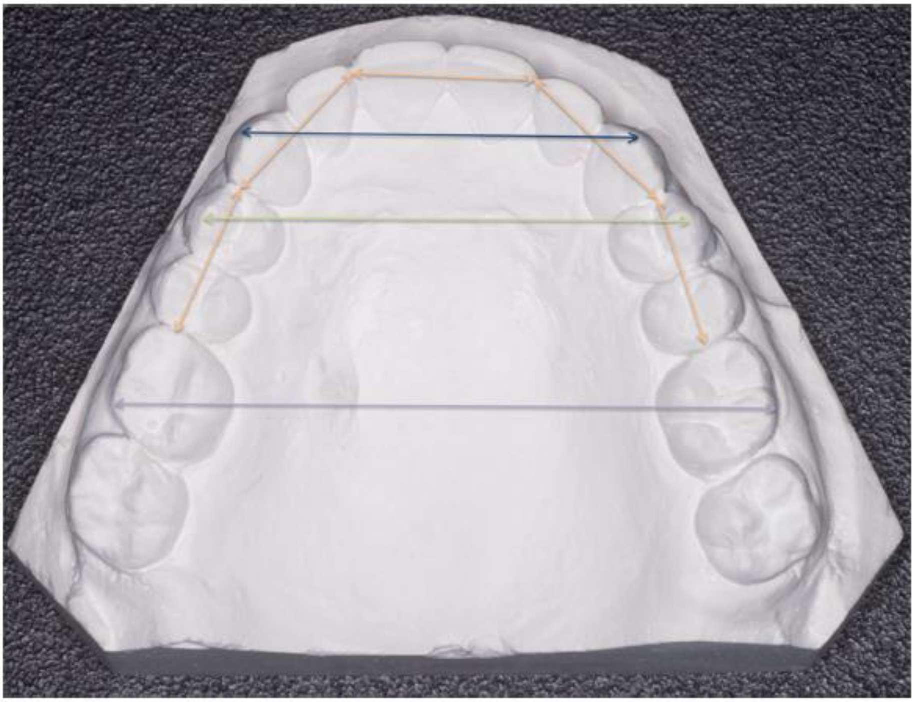

Fig. 1. Dental cast analysis. Blue line = inter canine distance, green line = inter premolar distance, purple line = inter molar distance, and orange line = arch length.

Statistical analysis

The statistical analysis was performed in association with the department of Biostatistics of the Erasmus MC, University Medical Center Rotterdam, the Netherlands . The analyses were performed using the Statistical Package of the Social Sciences (version 20.0, SPSS Inc, IBM Corporation). All measurements were performed twice by the author and the mean value was used for the analysis. The longitudinal changes were evaluated using Mixed Models ANOVA, with a boneferoni test. Because of the fact that during the follow-up period, other surgeries may have been performed, LeFort 1 osteotomy and teeth extractions were added as fixed factors in respectively the posterior-anterior cephalogram analysis and the dental cast analysis. A p-value of < 0.05 was considered significant.

Reliability analysis

To assess inter- and intra-observer agreement an intraclass correlation coefficient (ICC) was obtained. Therefore, all measurements were also done by the second author. An ICC value of ≥ 0.9 was considered reliable.

RESULTS

Baseline characteristics

A response rate of 40% was obtained and 17 patients of the initial 42 were included for the long-term follow-up. The mean age at the moment of surgery was 31, ranging from 13 to 47 years. The mean long-term follow-up time was 6.5 years, with a range of 5,1 to 8,7 years. Both bone- and tooth-borne distractors were equally distributed in this long-term cohort. These are the mean follow-up time points of T1, T2, T3 and T4: 2 months pre-operative, 2 months post-operative, 13 months post-operative and 78,6 months (6,5 years) post-operative. 9 patients underwent mandibular midline distraction simultaneously with the SARME. 4 patients underwent a le Fort I osteotomy during the follow-up period.

Dental cast study

See *Table 1 and 2* and **Fig. 2-4** for the complete results of the dental study casts measurements. A transversal dental expansion was obtained in all regions (canine, pre-molar and molar). The initial increase (T1-T2) was most profound in the premolar region with an increase 6.6 mm, in the canine and molar region an expansion of respectively, 6.3 and 5.5 mm was observed. After 1 year the expansion at the premolar level remained stable, however a insignificant decrease was measured in the canine and molar region of respectively: 2.5 and 1.3 mm. During the long-term follow-up little and non-significant decreases were observed in all regions.

Table 1. Distances.

	T1		T2		T3		T4		Time
	Mean (mm.)	S.E.	Mean (mm.)	S.E.	Mean (mm.)	S.E.	Mean (mm.)	S.E.	P-value
ICD	31.4	0.71	37.7	1.29	35.3	0.41	34.9	0.37	<0.001*
IPMD	35.7	0.93	42.3	0.92	42.7	0.61	42.0	0.63	<0.001*
IMD	46.8	1.24	52.3	1.14	51.0	0.83	50.8	0.78	<0.001*
AL	65.3	2.29	72.1	2.49	68.7	1.95	66.6	1.73	<0.001*
PWPM	13.0	1.1			16.0	0.89	16.7	0.71	<0.001*
PWMOL	15.6	0.99			18.5	0.82	18.4	0.63	<0.001*
PDPM	19.0	0.88			18.5	0.81	18.6	0.85	0.17
MM	60.6	1.39	63.0	0.85	62.9	0.99	61.8	0.98	0.007*
NN	17.5	1.75	18.1	1.40	18.2	1.25	18.2	1.52	0.91
Follow-up (months)	-2		2		13		78		

Dental cast study: Intercanine distance (ICD), interpremolar distance (IPMD), inter molar distance (IMD), arch length (AL), palatal width at premolar level (PWPM), premolar width at molar level (PWMOL), palatal depth at premolar level (PDPM) and palatal depth at molar level (PDMOL). Posterior-anterior cephalogram analysis: Inter molar distance (MM) and inter nasal base distance (NN). S.E.: standard error, * = P<0.05.

Table 2. Longitudinal results.

	T1-T2			T1-T3			T1-T4			T2-T3			T4-T3		
	Mean (mm.)	S.E.	P-value	Mean (mm.)	S.E.	P-value	Mean (mm.)	S.E.	P-value	Mean (mm.)	S.E.	P-value	Mean (mm.)	S.E.	P-value
ICD	6.3	1.14	<0.001*	3.9	0.57	<0.001*	3.5	0.57	<0.001*	-2.5	1.16	0.23	-0.3	0.33	1.00
IPMD	6.6	0.81	<0.001*	7.0	0.67	<0.001*	6.3	0.69	<0.001*	0.4	0.71	1.00	-0.7	0.49	0.89
IMD	5.5	0.89	<0.001*	4.2	0.81	<0.001*	4.0	0.83	0.001*	-1.3	0.78	06.1	-0.2	0.55	1.00
AP	6.9	1.18	<0.001*	3.4	1.01	0.013*	1.4	1.05	1.00	-3.5	1.20	0.049*	-2.0	0.85	0.13
PWPM				3.0	0.93	0.015*	3.7	0.55	<0.001*				0.6	0.74	1.00
PWMOL				2.9	0.59	<0.001*	2.8	0.60	0.001*				-0.1	0.48	1.00
PDPM				-0.5	0.29	0.225	-0.5	0.31	0.38				0.0	0.29	1.00
PDMOL				0.0	0.42	1.00	0.3	0.43	1.00				0.3	0.38	1.00
MM	2.4	0.82	0.063	2.3	0.73	0.046*	1.2	0.86	0.063	-0.1	0.26	1.00	-1.1	0.42	0.10
NN	0.6	1.08	1.00	0.7	1.08	1.00	0.8	1.16	1.00	0.1	0.78	1.00	0.1	1.01	1.00

Longitudinal results dental cast study: Intercanine distance (ICD), interpremolar distance (IPMD), inter molar distance (IMD), arch length (AL), palatal width at premolar level (PWPM), premolar width at molar level (PWMOL), palatal depth at premolar level (PDPM) and palatal depth at molar level (PDMOL). Longitudinal results posterior-anterior cephalogram analysis: Inter molar distance (MM) and inter nasal base distance (NN). S.E.: standard error, * = P<0.05.

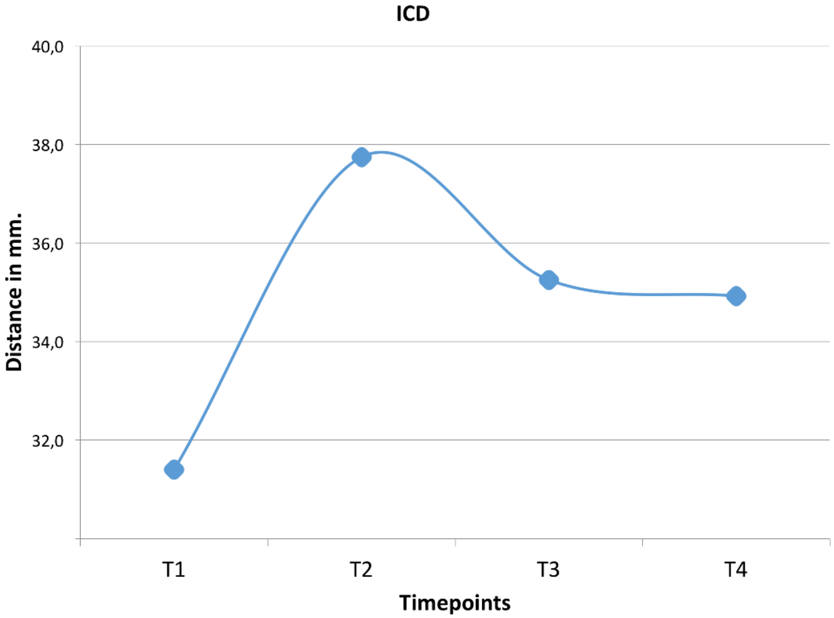

Fig. 2. Intercanine distance (ICD).

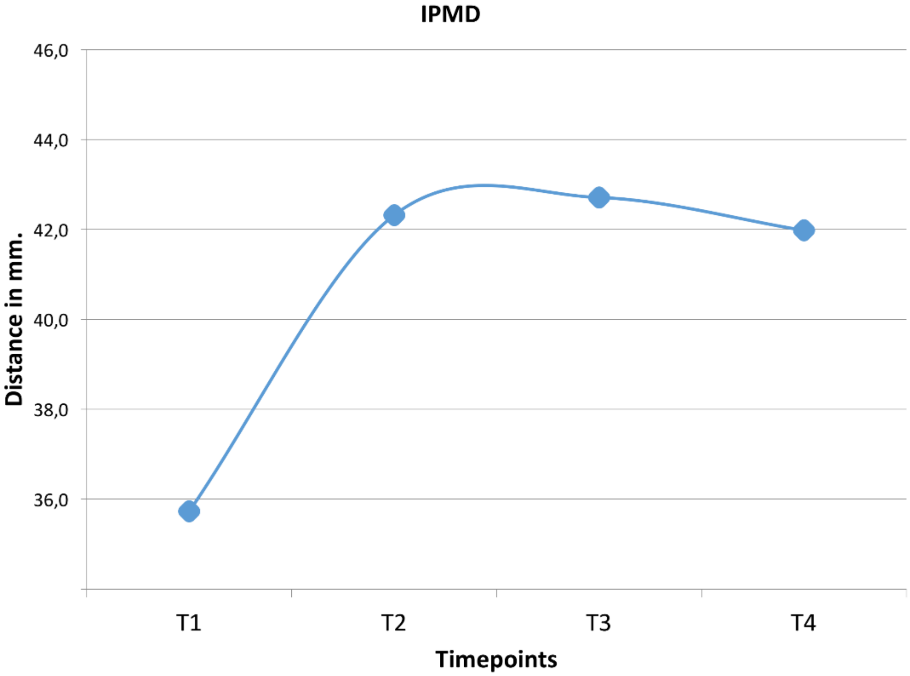

Fig. 3. Interpremolar distance (IPMD).

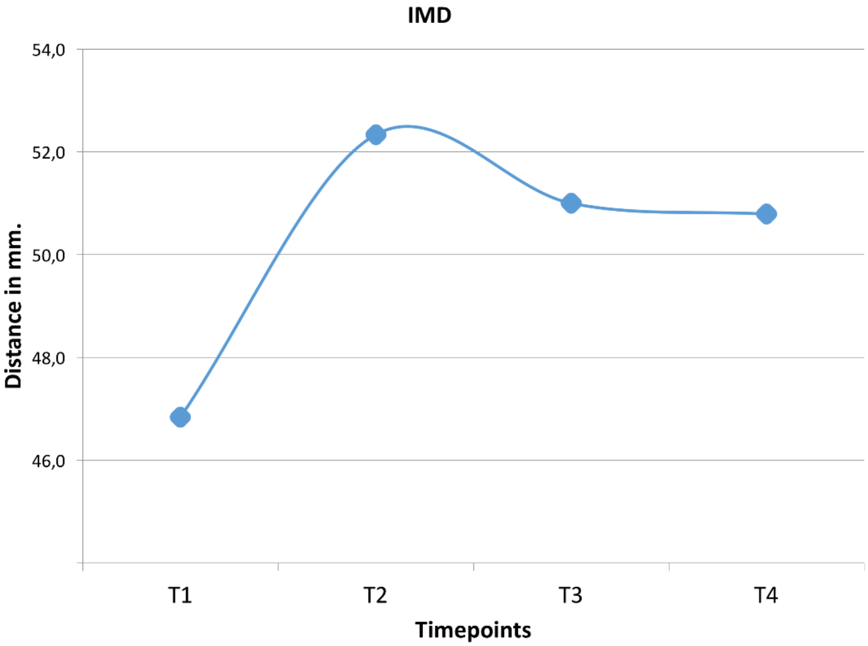

Fig. 4. Intermolar distance (IMD).

An initial significant increase in arch length was obtained of 6.9 mm (T1-T2), however after 1 year a decrease of 3.5 mm (T2-T3) was measured and during the long-term follow-up it decreased 2 mm (T4-T3).

Regarding palatal width, a significant and stable increase was obtained in the long-term of 3.7 and 2.8 mm (T1-T4), respectively in the premolar and molar region. No significant effect of SARME on the palatal depth was observed.

Posterior-anterior cephalograms analysis

See *Table 1 and 2* for the complete results of the posterior-anterior cephalogram analysis. In the molar region an initial increase was observed of 2.4 mm (T1-T2), however between T1 and T4 the increase was 1.2 mm and not significant. No significant effect of SARME was seen in nasal region. The control measurement between the zygomas remained stable.

Reliability analysis

The ICC for each separate measurement were ≥ 0.9 indicating reliable measurements for both the inter- and intra-observer.

DISCUSSION

Surgically assisted rapid maxillary expansion (SARME) is a well-established and relatively safe surgical technique to widen the maxilla[10, 11]. This study is a continuation of the study of Koudstaal et al. on stability, tipping and relapse between tooth- and borne-distractors in SARME[7]. In the original study no significant differences were found between the two types of distractors, and this is further substantiated by recent research[12, 13]. In our clinic this study caused a shift towards an almost exclusive use of tooth-borne distractors in non-syndromal patients with transverse maxillary hypoplasia. Preferably, this study would have included all of the previously included patients, however despite the greatest effort of the researchers to invite as much patients as possible, the number of patients that responded to our recall was too little to compare the two distractor groups. Nonetheless, this study gives a good perspective on the long-term effects of SARME in a prospective patient cohort. Long-term follow-up studies on SARME do exist, however most of the study are relatively limited in follow-up time or do not include a 1-year post-operative timepoint. This study attempt to more insight in the dental and skeletal changes after SARME and orthodontic treatment.

To achieve a stable result in SARME, it is necessary to achieve a solid bony fundament for the dentition. In non-growing patients, different bony structures resist effective maxillary expansion. These bony structures include: pterygoid plates, crista zygomatico-alveolaris, appertura piriformis, and to a lesser extent the midpalatal suture[14]. With SARME some or all of these structures are released in order to be able to widen the maxilla. Surgeons differ in their operations techniques, some advocate releasing as much resistance as possible, others like to be less invasive[15]. The greatest difference between the techniques is the use of a pterygoid plates osteotomy. Biomechanically, with the release of the pterygoid plates the most posterior resistance for expanding the maxilla is weakened and therefore a more parallel widening pattern of the maxilla is to be expected. Seeberger et al. states that a transverse shift of segments can be achieved without an osteotomy of the pterygoid plates[16]. Goldenberg et al. suggest only to release pterygoid plates in cases the widening is desired in the posterior part of the maxilla[17]. In addition to the biomechanical aspects, other aspects should be important in the choice for a technique. Surgically the pterygoid osteotomy can be more challenging, with an increased risk of injuring the pterygoid plexus and bleeding. An increase in morbidity is expected as well, since the operation field is larger.

The long-term results of this study are in line with the previously described studies on the long-term effect of SARME on widening the maxilla [18-20]. Magnussen et al. and Anttila et al. described their long-term experiences with SARME, including a ptyergoid disjunction

[18, 20]. No significant relapse was found after the orthodontic treatment was completed with a mean follow-up of 4.7 years for Anttila et al and 6.4 years for Magnussen et al.[18, 20]. This present study shows that without performing a pterygoid disjunction long-term stable results can be achieved as well. Although the long-term expansion of the maxilla is approximately 0.5-1.5 mm less in the molar region compared to the premolar and canine region, a good and stable occlusion was achieved.

Another aspect for debate is the distractor type. The different distractors apply their forces differently, and create different vector. A tooth-borne distractor applies the forces at dental level, with two or four contact points on each segment, providing a stable vector on a less stable fixation point: teeth. As the distractor is fiaxated on teeth it may cause orthodontic movement, and depending on the amount of dental response this could lead to bone fenestration of the teeth, gingival recessions, periodontal problems, root resorption, and dental tipping[21]. A bone-borne distractor applies the forces at the bone cranial to the teeth with one contact point on each segment. The one-point fixation can cause a rotational movement of the segments and an asymmetric widening can be found. Asymmetrical widening might increase the need for extensive orthodontic treatment. Furthermore, a second procedure is needed to remove a bone-borne distractor, which is a higher burden for the patient and less cost-effective. Although no discrimination was made between the two distractors in this long-term follow-up study, the combination of the previous studies and the absence of relapse in our combined cohort indicates no difference between the distractor in terms of stability. In our experience, SARME with a tooth-borne distractor is adequate in most patients. In extreme cases, for a example a very narrow palate with too little space for a tooth-borne distractor, short radices or periodontal compromised teeth, the surgeon can choose for a bone-borne distractor.

The time points chosen in this study provides insight in the amount of relapse after activation and removal of the distractor. While most long-term studies focus on the retention phase after orthodontic treatment, this study illustrates the amount of relapse and the time-frame when most relapse occur. Most of the relapse was observed between T2 and T3, in the period that orthodontic treatment took place. This is effect is probably more a result of the dental decompensation during the orthodontic treatment, and not specific relapse of the maxillary widening. After this phase minimal relapse was observed indicating a stable result of SARME in the long-term, even long after orthodontic treatment was finished. In the canine region the largest amount of ‘relapse’ was observed, which is a result of intended orthodontic treatment to close the distraction gap. After orthodontic treatment the intercanine distance remained stable. The greatest widening during the long-term follow-up was gained in the premolar region, and as previously mentioned less widening was achieved in the molar and canine region.

Regarding palatal width, a stable increase was observed, similar to the dental width. This indicates a bony expansion after SARME. Palatal depth was not significantly affected by SARME in this study. During the initial study, a significant loss palatal depth was observed in the molar region using a bone-borne distractor. Since both groups were put together in this study it could not be reproduced.

In this study posterior-anterior cephalograms were used to study the effects of SARME on bone level in the molar and nasal base region. The results show, apart from initial increase in the molar region (T1-T3, $P < 0,05$), no significant effect. In theory, the use of a bone-borne distractor should result in more bony expansion since the distractor applies the force cranially. In the Koudstaal et al. study no difference between the two distractors was seen in maxillary tipping[7]. It appears that the maxillary tipping which occurred did not affect the relapse of the transversal dental measurements.

With new imaging techniques being integrated in most treatment protocols nowadays, more specific measurements can be made. Zandi et al. conducted a study with the use of CBCT on palatal depth and width, nasal floor and dental effects. They confirm our findings that the effects of SARME are more profound on the dental level and less in the nasal region[12]. Also, they did not find significant differences with the use of a bone- or tooth-borne distractor.

This study showed that SARME is a predictale technique to widen the maxilla, with stable results on both dental and skeletal level in the long-term. Future research on the (long-term) effects of SARME should incorporate 3D imaging techniques and focus on the skeletal and soft tissue effects, preferably in a randomized controlled trial comparing surgical techniques and distractors.

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Patient experience and satisfaction after surgically assisted rapid maxillary expansion and mandibular midline distraction

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ABSTRACT

Little is known regarding patient experience and satisfaction of surgically-assisted rapid maxillary expansion (SARME) and mandibular midline distraction (MMD). This study therefore aims to assess patient experience and satisfaction of these techniques in two different groups. The first group answered the post-surgical patient satisfaction questionnaire on a 7-point Likert-scale during a long-term follow-up recall. The second group answered a visual analog scale-questionnaire (ranging from 0-10) with different questions regarding experience and satisfaction, at different time points during the first year of treatment. In both groups 17 patients were included. Regarding the post-surgical patient satisfaction questionnaire, a mean satisfaction rate of 6.4 (range: 4-7) was reported, with a mean follow-up of 6.5 years post-operatively. In the visual analogue scale group, the mean satisfaction rate was 8.0 and did not significantly differ from the expectations pre-operative ($P = 0.96$). Both procedures showed relatively low pain scores, although a significant higher score was observed in MMD post-operative ($P = 0.00051$). Regarding hindrance, the scores were moderate, whereby the, bone-borne distractor in the mandible gained higher scores than the tooth-borne distractor in the mandible. In conclusion, both SARME and MMD gain high satisfaction rates.

INTRODUCTION

Surgically-assisted rapid maxillary expansion (SARME) and mandibular midline distraction (MMD) are surgical methods to widen respectively the maxilla and mandible. Indications include anterior crowding, posterior crossbite and buccal corridors. In addition, preliminary to secondary orthognathic (e.g. bilateral sagittal split osteotomy (BSSO) and Le Fort I osteotomy) surgery SARME and MMD might be indicated. The technique involves a surgical intervention and intensive contact between patient, surgeon and orthodontist. Post-operatively, a patient will experience a period with swelling, pain and during the distraction phase an esthetically disturbing diastema between the upper or lower incisors appears. This can all be quite uncomfortable for a patient. So far research mainly focused on the biomechanical parameters and surgical technique and outcome, which both have proven to be highly effective and stable in the long-term. Low complication rates are reported in the literature. Complications are mild, transient, and manageable without the need for any reoperation[1-6]. However, little is reported on expectations and perceptions of patients during and at the end of these treatments. This study aims to assess patient experience and satisfaction during and after SARME and MMD. These clinical outcomes are relevant for orthodontists and surgeons in their choice of treatment.

MATERIAL AND METHODS

This study was conducted after approval had been given by the Standing Committee on Ethical Research in Humans of the Erasmus MC, University Medical Center Rotterdam, the Netherlands (MEC 2011-265 and MEC-2013-367).

Post-surgical patient satisfaction questionnaire

The first group consisted of patients who underwent SARME between 2004 and 2008. The patient cohort was derived from the study on the long-term effects of SARME performed in the Erasmus MC, University Medical Center Rotterdam, the Netherlands[7]. During the long-term follow-up patients were asked to fill in the post-surgical patient satisfaction questionnaire (PSPSQ) as proposed by Posnick et al. (*Appendix I*)[8]. The questionnaire is specifically designed to assess the patient satisfaction after orthognathic treatment. The PSPSQ consists of nine statements on which the patient states his/her agreement on a 7-point Likert-scale. The scale ranged from unsatisfied to neutral to very satisfied, a score of 4 is considered neutral. Due to the fact that some patients were treated with other orthognathic surgical interventions, they were asked to answer the question only regarding SARME. A translated version into the Dutch language of the original questionnaire was used.

Visual analogue score questionnaire

The second group consisted of patients who underwent SARME and MMD between 2010 and 2012. Inclusion criteria for this group were: maxillary and or mandibular discrepancy (uni- or bilateral crossbite, maxillary anterior and/or posterior crowding buccal corridors). Exclusion criteria for this group were: congenital (craniofacial) deformity patients; incomplete records; history of radiation therapy in the area of interest; aged under 16 years; mental retardation. In general, a tooth-borne distractor was used in SARME and a bone-borne in MMD. Patients were asked to fill in a visual analogue scale questionnaire (VAS) on how they perceive the treatment. The design of the questions made it possible to score the same question during the entire treatment period. A score was given on a 10 cm. VAS-scale (*Table 1*). The following topics were included: satisfaction regarding dental appearance (VAS-score, question 1) and appearance of mouth (VAS-score, question 2), expected and experienced hindrance of the distractor (VAS-score, question 3, 4), expected and experienced impact of the surgery (VAS-score, question 5), expectation and satisfaction with total outcome (question 6) and experience of pain (VAS-score, question 7 and 8). Questions 3 and 7 only apply for SARME and questions 4 and 8 only apply MMD. At different time points the questionnaires were obtained, namely: T1: pre-operatively, T2: direct post-operatively, T3: at stop of distraction, T4: 3 months post-distraction and T5: 12 months post-operatively.

Table 1. Visual analogue scale (VAS) questions, translated to English.

VAS questions	
Question 1	How satisfied are you with your dentition?
Question 2	How satisfied are you with your mouth?
Question 3	How much hindrance do you expect to have of the maxillary distractor? How much hindrance do you have of the maxillary distractor? How much hindrance did you had of the maxillary distractor?
Question 4	How much hindrance do you expect to have of the mandibular distractor? How much hindrance do you have of the mandibular distractor? How much hindrance did you had of the mandibular distractor?
Question 5	How radical do you expect the surgery to be? How radical was the surgery?
Question 6	How satisfied do you expect to be with result? How satisfied are you with the result?
Question 7	How much pain do you experience pain of the maxilla?
Question 8	How much pain do you experience pain of the mandible?

Statistical analysis

The longitudinal data (VAS-scores) were analyzed using a linear mixed model analysis whereby the T1 is regarded as baseline (R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.). A *P*-value < 0.05 was regarded as significant.

RESULTS

PSPSQ

In the PSPSQ study group 17 of the 42 patients responded and completed the questionnaire, see *Table 2*. The mean follow-up time was 6.5 years. Besides SARME, 9 patients underwent MMD; 2 patients a BSSO; and 4 patients a bimaxillary osteotomy. A mean of 6.4 (standard deviation: 0.9; range: 4-7) was given regarding overall satisfaction, and none of the patients reported less than 4. For the complete outcome see *Table 3*.

Table 2. Baseline patient characteristics.

	PSPSQ	VAS
Mean age at surgery (range)	31 (18-47)	31 (17-49)
Male/Female	♀: 10, ♂: 7	♀:10,♂: 7
MMD	BB: 9	TB: 3; BB: 14
SARME	TB: 8; BB: 9	TB: 17

BB: bone-borne distractor, TB: tooth-borne distractor.

Table 3. The results of the PSPSQ.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Mean	5.8	5.8	6.4	6.1	5.8	5.7	6.0	6.1	6.3
SD	1.8	1.3	0.9	0.9	1.1	1.0	1.2	1.1	1.0
Range	2-7	3-7	4-7	4-7	3-7	3-7	2-7	4-7	4-7

VAS

In the VAS-group 17 patients were included of which 16 patients received both SARME and MMD, 1 patient was treated with MMD only, see *Table 2*. For the complete results see *Table 4* and **Fig. 1**. Noticeably, is the increase in VAS-score for patients after T3 regarding dentition and appearance of mouth, whereby the increase regarding dentition is significant for T4 and T5 (*P* < 0.05). The satisfaction of patients with their dentition was statistically higher than patients expected. The hindrance score for the tooth-borne distractor used in the maxilla is lower than the bone-borne distractor used in the mandible.

Regarding the impact of the procedures, the lowest scores were given at T3 and T4 and were significant ($P < 0.05$). The overall satisfaction remains stable at a score of around 8 and did not differ significant from the pre-operative expectations ($P > 0.05$). The pain score for the mandible was post-operatively significantly higher than was expected ($P < 0.05$). In addition, the given scores for the mandible were higher than for maxilla.

Table 4. Mean scores on VAS-questionnaire.

	T	Vas-score	p-value	
Question 1	T1	3,0		
	T2	2,4	0,4462	
	T3	4,3	0,0774	
	T4	5,1	0,0044	**
	T5	5,9	0,0017	**
Question 2	T1	4,8		
	T2	4,6	0,828	
	T3	4,0	0,325	
	T4	5,7	0,222	
	T5	6,5	0,052	
Question 3	T1	4,8		
	T2	4,4	0,64	
	T3	3,9	0,3	
	T4	3,8	0,23	
	T5	3,9	0,4	
Question 4	T1	5,4		
	T2	5,4	0,99	
	T3	4,6	0,29	
	T4	5,3	0,92	
	T5	5,3	0,98	
Question 5	T1	5,3		
	T2	4,1	0,0871	
	T3	3,1	0,0018	**
	T4	4,0	0,0381	*
	T5	5,0	0,6887	
Question 6	T1	8,0		
	T2	7,5	0,47	
	T3	7,2	0,27	
	T4	8,0	0,96	
	T5	7,6	0,65	

Table 4. Mean scores on VAS-questionnaire. (continued)

	T	Vas-score	p-value	
Question 7	T1	1,8		
	T2	1,9	0,919	
	T3	1,0	0,146	
	T4	1,1	0,222	
	T5	0,1	0,025	*
Question 8	T1	1,4		
	T2	3,5	0,00051	***
	T3	1,5	0,95657	
	T4	1,7	0,65168	
	T5	0,2	0,06831	

T: time point, *: *P*-value = <0,05; **: *P*-value = <0,001, ***: *P*-value = <0,0001.

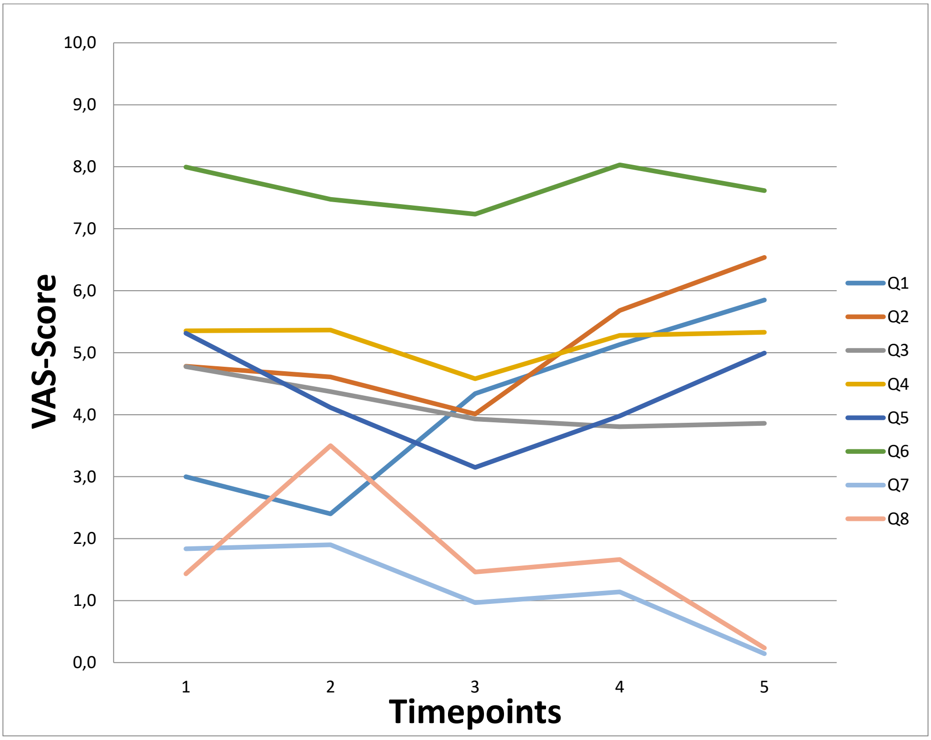

Fig. 1. Visual VAS-scores of the different questions (Q1-Q8) at different time points.

DISCUSSION

In this study patients who underwent MMD and SARME were examined on their expectations and satisfaction. Both procedures showed high satisfaction scores in both the

PSPSQ and VAS questionnaires. Relatively low pain scores were observed, although a significant higher score was seen in MMD post-operative ($P < 0.05$). Regarding hindrance, the scores were moderate, whereby regarding the mandible, the bone-borne distractor gained higher scores than the tooth-borne distractor.

In literature, studies assessing patient satisfaction following orthognathic surgery are relatively uncommon, specifically studies regarding SARME and MMD are scarce[9-11]. In recent years, a shift towards a more holistic view on (surgical) treatments appears in literature and not only biomechanical aspects are deemed to be essential. Researchers have focused on complication rates, costs effectiveness and patient satisfaction[12]. Assessment of patient satisfaction is not only important for surgeons to improve their treatment, it is also viable for future patients so they can be well informed. In addition, value based health care initiatives advocate registration of outcome measurements including patients satisfaction as it will improve quality and curb inefficiencies[13].

PSPSQ

The PSPSQ results indicate that all patients that underwent SARME are very satisfied with the treatment and no patient was dissatisfied. However, not every patient in our study would advise the treatment to others (PSPSQ, question 2) and/or would undergo the treatment again (PSPSQ, question 1). This might indicate that patients experience the treatment as demanding and intense. This suggests, even when there is a good indication for treatment, careful patient selection is advisable to avoid disappointed patients.

Regarding the questions specifically focused on orthognathic surgery, all questions were rated above average. The questions regarding bite, sensory disturbances and temporomandibular joint/facial pain were the best rated questions. Improvement of the bite is one of the foundations of orthognathic surgery, the high score combined with no patients scored under 4 indicates that SARME has a positive influence on bite and underpins the indication for SARME. Regarding joint and facial pain the high score implicates that SARME has little effect on these factors after the normal healing period. Biomechanically it would be very surprising if temporomandibular joint pain would occur, since no surgery is performed on the mandible and the joints are theoretically not loaded differently. However, due to surgical and orthodontic treatment the occlusion changes, which might attribute to this observation. The score for sensory disturbances is related to chin and lower lip disturbances and are less relevant for this study. Primarily because it is physically not related to the surgical field, the score might be affected due to the other surgeries that were performed in that region such as BSSO or MMD.

The questions concerning breathing, articulation and speech had a mean score ranging between 5.7 and 6.0. Breathing might be affected by SARME as it enlarges the nasal cavity and could therefore attribute to improved breathing[14]. Notably articulation and speech would be an important aspect to discuss pre-operatively as they were the lowest reported scores. Although the scores are above average it might imply that after SARME speech and articulation are affected.

VAS

In general, patients were satisfied with the overall results and these met their expectations. Satisfaction scores during the treatment ranged between 7.2 and 8.0 and are in concordance with the long-term results of the PSPSQ. Regarding dentition and appearance of the mouth, an increase in scores was found, with an initial decrease during the post-surgical and distraction phase. Although SARME seems to have a positive effect on these parameters, the end scores for dentition and appearance of mouth were 5.9 and 6.5. These results might be affected due to the fact that 8 patients needed secondary orthognathic surgery and therefore scored lower on these parameters. A large separate group that only would consist of patients who do not need secondary orthognathic surgery, would overcome this bias.

The results regarding the hindrance of distractors show that these tend to be mildly uncomfortable for patients, with the distractors used in the mandible tending to be more distressful than the ones used for SARME. The same is observed in pain scores, which are relatively low, with an increase post-operative. The relative low score can be attributed due to the fact that patients were administered analgesics post-operatively. In MMD, the position of bone-borne distractors penetrating the mucosa increases the risk of dehiscence and the close relation to the lips can attribute to pain and hindrance for patients. In our department, these findings contributed to the decision to preferably use tooth-borne distractor in MMD. Future research is necessary that clarifies the biomechanical differences in types of distractors used for MMD.

Patients estimate the severity of the procedure as medium, although the scores are higher before and at the 1 year follow up. This would be explained by the fact that patients report the lowest severity score just after the distraction is finished. At this point they might assume that everything is ‘normal’ again and not realize a healing and consolidation period is still needed. Whereby the distractors are still in place, a soft diet is indicated and a diastema might be noticeable between the incisors. One of the aims of this study is to assess the experience of patients during the procedures allowing surgeons and orthodontists to better inform patients. The above suggests that in our clinic patients should perhaps be better informed considering the period after the distraction phase.

In accordance with our study, Gareau et al. and Rocha et al. report high satisfaction rates in patients who underwent SARME using self-made questionnaires[15,16]. However, no study was performed that monitored patients undergoing SARME and MMD in one operation. The study Gareau et al. presented the patient experience using bone-borne and tooth-borne distractors[16]. They concluded that use of a bone-borne distractor was prevailed in favor of a tooth-borne distractor. Mainly because patients report the bone-borne distractor to be easier to use and that all patients who used a tooth-borne distractor needed help from another person. This is, however, not our own experience. In addition, due to the jack-screw configuration of the bone-borne distractor used in their study, a specific activation pattern is needed, which could potentially cause misuse of the distractor[16]. Due to the similar biomechanical effects, no need for surgical removal and shorter operation time, we advocate a tooth-borne device. Rocha et al. advocate pre-operatively counseling in order to get patients' expectations in line with the normal course of treatment program, this is in accordance with findings of this study[15].

Recently Baranto et al. reported the satisfaction outcomes using a self-made questionnaire on 30 patients who underwent SARME with a combined bone- and tooth-borne (hybrid) distractor. Twenty-nine of these patients were satisfied with this treatment and had no regrets. Other preoperative difficulties like biting, chewing, dental position, facial appearance, speech and self-esteem had improved with this treatment according to most of the patients. Worsening of pain in the TMJ region was uncommon among the patients (6.7%)[17]. These findings are broadly in line as well with our own experience.

Few limitations of this study need to be addressed. First, although the used questionnaire has been used previously to evaluate patient satisfaction regarding complex orthognathic surgery[8], it has yet not been validated which is a major limitation. Second, there might be a selection bias because the response rate in our study was relatively low. This might have biased our results and can lead to limited generalizability. Third, responses to questionnaires taken at the long-term might be affected by additional orthognathic surgery and can be subject to recall bias.

CONCLUSION

In our study, despite the limitations, patients who underwent SARME and MMD to widen respectively the maxilla and mandible are satisfied with their treatment. This finding could support orthodontists and surgeons in their choice of treatment.

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Post Treatment Questionnaire

(Please circle your response to each question)

If you had to make the decision again, how likely would you be to undergo this same surgery?

1	2	3	4	5	6	7
Not at all			Neutral			Very Likely

How likely would you be to recommend this same surgery to others?

1	2	3	4	5	6	7
Not at all			Neutral			Very Likely

Considering everything, how satisfied are you now with the results of surgery?

1	2	3	4	5	6	7
Not at all Satisfied			Neutral			Very Satisfied

Overall, how satisfied are you with your current bite?

1	2	3	4	5	6	7
Not at all Satisfied			Neutral			Very Satisfied

Overall, how satisfied are you with your current speech articulation?

1	2	3	4	5	6	7
Not at all Satisfied			Neutral			Very Satisfied

Overall, how satisfied are you with your current lip posture and lip closure?

1	2	3	4	5	6	7
Not at all Satisfied			Neutral			Very Satisfied

Overall, how satisfied are you with your current breathing?

1	2	3	4	5	6	7
Not at all Satisfied			Neutral			Very Satisfied

Overall, how accepting are you with your current level of TMJ / facial pain

1	2	3	4	5	6	7
Not at all Accepting			Neutral			Very Accepting

Overall, how accepting are you with your current level of lower lip/chin sensation

1	2	3	4	5	6	7
Not at all Accepting			Neutral			Very Accepting

Appendix I. Post-surgical patient satisfaction questionnaire (PSPSQ).

IV

SURVEY AND COMPLICATIONS

9

Current practice for transverse mandibular and maxillary discrepancies in the Netherlands: A web-based survey among Orthodontists and Oral and Maxillofacial Surgeons

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ABSTRACT

The main objective of this study was to provide an overview of the current practice for transverse mandibular and maxillary discrepancies in the Netherlands using a web-based survey. Orthodontists (ORTHO) and Oral and Maxillofacial Surgeons (OMFS) in the Netherlands were invited to the web-based survey via their professional association. Three cases were presented which could be treated non-surgically and surgically. Participants were asked what treatment they preferred: no treatment, orthodontic treatment with optional extractions or surgically assisted orthodontic treatment. The web-based survey ended with questions on various technical aspects and any experienced complication. Invitation was sent to all 303 members of professional association for ORTHO and to all 379 members of professional association for OMFS. Overall response number was 276 (response rate of 40.5%), including 127 incomplete responses. Generally, ORTHO prefer orthodontic treatment with optional extractions and OMFS lean towards surgically assisted orthodontic treatment. Mandibular Midline Distraction appears to be less preferred, possibly due to lack of clinical experience or knowledge by both professions despite being proven clinical stable surgical technique with stable long-term outcomes. There seems to be consensus on technical aspects by both professions, however, there are various thoughts on duration of consolidation period. Complications are mostly minor and manageable.

INTRODUCTION

Historically, transverse mandibular and maxillary discrepancies were managed with orthodontic dental expansion and/or dental extraction therapy. Changes in arch dimensions by dental expansion result in unstable post-treatment results. The mandibular symphysis closes at 1 year of age[1,2], which makes expansion without surgery impossible. The midpalatal suture can be expanded with orthodontic treatment until approximately the age of 15[3]. With the introduction of distraction osteogenesis for the facial skeleton in 1990, new treatment options became possible[4,5]. Both osteogenesis and histogenesis are induced with this technique.

Mandibular midline distraction (MMD) is a proven surgical technique to widen the mandible in order to solve transverse mandibular discrepancies with stable long-term outcomes[6,7]. In conjunction with an osteotomy in the midline of the mandible a distractor is attached on both sides of the osteotomy, after which the skeletal dental base can be expanded by distraction osteogenesis. General indications for MMD are V-shape of the mandible, anterior or posterior crowding, uni- and bilateral crossbite and impacted anterior teeth with inadequate space and tipped teeth[5,8-10]. For maxillary transverse discrepancies, surgically assisted rapid maxillary expansion (SARME) is a widely applied stable technique[11,12]. Clinically, indications for SARME include anterior or posterior crowding, uni- and bilateral crossbite, black buccal corridors, buccal tipping of the maxillary molars and lingual tipping of the mandibular molars[11-13].

There are various types of distractors available such as tooth-borne, bone-borne or a combination of both (hybrid). Following surgery, generally a latency period is respected to create soft callus formation before starting with distraction. In contrast to distraction technique for the long bones[14], there is no standardized protocol for MMD and SARME. In the literature, there are many variable factors like the clinical indication, anesthesia technique, osteotomy technique (MMD: vertical or step, SARME: surgical transections), latency period, distractor type, distraction rate, overcorrection and consolidation period.

The main objective of this study was to provide an overview of the current practice for transverse mandibular and maxillary discrepancies in the Netherlands using a web-based survey. Orthodontists and Oral and Maxillofacial Surgeons can use this information to align and improve the treatment modalities for transverse mandibular and maxillary discrepancies and inform their patients better about the possible treatment options.

MATERIALS AND METHODS

Orthodontists and Oral and Maxillofacial surgeons in the Netherlands were invited per mail to participate anonymously in this web-based survey after approval had been obtained from the Medical Ethics Committee of Erasmus MC, University Medical Center Rotterdam, the Netherlands (approval number: MEC-2020-0459). This was provided by using the professional associations for Orthodontists (*‘Nederlandse Vereniging van Orthodontisten’*, NVvO) and for Oral and Maxillofacial Surgeons (*‘Nederlandse Vereniging voor Mondziekten, Kaak- en Aangezichtschirurgie’*, NVMKA). To maximize the response rate, the invitation to participate was sent twice to the same mail list by both professional associations and the web-based survey was built with tick box answers.

In this web-based survey participants were asked what specialism they practice, what their place of training was, how many years of experience they have and if they are practicing in a training clinic.

Three cases were presented clinical and radiographic with transverse mandibular and maxillary discrepancies that can be treated both non-surgically and surgically (*Appendix I, II, III*).

Case 1 was a 16-years old woman, *case 2* a 44-years old man and *case 3* a 43-years old man. The patients’ chief complaint was explicitly not mentioned in order to disclose an unbiased treatment planning decision.

All three presented patients had given prior written consent for the use of their visual material for this web-based survey and publication in a scientific journal.

Participants were asked what treatment they prefer with the following answer options:
- No treatment.

- Orthodontic treatment with optional extractions:
  - o Without premolar extractions in the lower and upper jaw, only orthodontic alignment of both dental arches.
  - o With premolar extractions only in the lower jaw, followed by orthodontic alignment of both dental arches.
  - o With premolar extractions only in the upper jaw, followed by orthodontic alignment of both dental arches.
  - o With premolar extractions in both the lower and upper jaw, followed by orthodontic alignment of both dental arches.

- Surgically assisted orthodontic treatment:
  - Surgically assisted expansion of the lower jaw only with distraction osteogenesis, followed by orthodontic alignment of both dental arches.
  - Surgically assisted expansion of the maxilla only with distraction osteogenesis, followed by orthodontic alignment of both dental arches.
  - Surgically assisted expansion of both the lower and upper jaw with distraction osteogenesis followed by orthodontic alignment of both dental arches.

After giving the preference of treatment, our applied treatment(s) were shown for each case separately. *Case 1* was treated with surgically assisted orthodontic treatment: with MMD using a bone-borne (Rotterdam Mandibular) distractor and with SARME using a Hyrax distractor. *Case 2* was treated with surgically assisted orthodontic treatment: with MMD using a tooth-borne distractor and with SARME using a Haas distractor. *Case 3* was treated with orthodontic treatment with premolar extractions in both the lower and upper jaw followed by orthodontic alignment of both dental arches.

In addition, participants were asked if they were satisfied with our applied treatment by using a score scale (1 = very dissatisfied and 5 = very satisfied) and whether they will recommend (again) the applied treatment in the future for the same indication.

The web-based survey ended with questions on various technical aspects concerning the number of surgically assisted orthodontic treatment performed, preference of distractor type, latency period, distraction rate, overcorrection, consolidation period, orofacial soft tissue effects and any experienced complication.

All the obtained data were stored automatically and anonymously in LimeSurvey GmbH, version 2.06lts Build 160524, which is provided by the local Erasmus MC server.

Statistical analysis

Descriptive statistics are used to characterize the study population. Means are presented for data that followed a normal distribution and medians if the data followed a non-normal distribution. The presented proportions are based on the number of valid cases.

For data handling and analyses, the Statistical Package of Social Sciences version 25.0 for Windows (IBM Corp, Armonk, NY, USA) was used. The graphical figures were made by exporting the data to Microsoft Excel 2016 for Windows version 16.0 (Microsoft, Redmond, WA, USA). In reporting of this study the STROBE guidelines were followed[15].

RESULTS

This web-based survey was sent per mail twice to all 303 members of the NVvO (Orthodontists, ORTHO) and to all 379 members of the NVMKA (Oral and Maxillofacial Surgeons, OMFS). There was an overall response number of 276 (response rate of 40.5%), including 127 incomplete responses. See *Table 1* and **Fig. 1-3** for a complete overview of the responses and results per case.

Table 1. Complete overview of the responses and results per case.

	OMFS (*n* = 379)	**ORTHO** (*n* = 303)
Responses *(overall n* = 276*)* **(40.5%)**	**113 (29.8%)**	**150 (49.5%)**
Work experience as a specialist:		
Less than 5 years	38	25
Between 5-10 years	25	21
Between 10-15 years	14	27
More than 15 years	32	59
Resident in training	11	16
No longer working	3	2
Place of education:		
‘Vrije Universiteit’ Amsterdam	14	36
‘Academisch Medisch Centrum’ Amsterdam	10	-
‘Universitair Medisch Centrum’ Utrecht	14	-
‘Universitair Medisch Centrum’ Leiden	5	-
‘Universitair Medisch Centrum’ Maastricht	4	-
‘Universitair Medisch Centrum’ Groningen	23	27
‘Radboud Universiteit’ Nijmegen	19	47
‘Erasmus Medisch Centrum’ Rotterdam	15	-
Other	5	29
Total	109	139
Practicing in a training clinic:		
No	52	113
Yes/partially	46	19
Not anymore	1	-
Total	99	132
Case 1 (n)	**90**	**135**
Treatment		
Orthodontic treatment	**45 (50%)**	**118 (87.4%)**
Without PM extractions	17 (37.8%)	47 (39.8%)
With PM extractions LJ+UJ	16 (35.6%)	69 (58.5%)
With PM extractions LJ	10 (22.2%)	2 (1.7%)

Table 1. Complete overview of the responses and results per case. (continued)

	OMFS (*n* = 379)	**ORTHO** (*n* = 303)
With PM extractions UJ	2 (4.4%)	0 (0.0)
Surgically assisted orthodontic treatment	**39 (43.3)**	**10 (7.4%)**
MMD	2 (5.1%)	0
SARME	22 (56.4%)	5 (50%)
Both	15 (38.5%)	5 (50%)
No treatment	**6 (6.7%)**	**7 (5.2%)**
Satisfaction		
Mean ± SD	3.67 ± 1.00 (*n* = 67)	3.50 ± 1.01 (*n* = 100)
Recommend (again) the applied treatment		
Yes	27 (40.3%)	15 (15.0%)
No	40 (59.7%)	85 (85%)
	67	100
Case 2 (n)	**79**	**119**
Treatment		
Orthodontic treatment	**32 (40.5%)**	**73 (61.3%)**
Without PM extractions	9 (28.1%)	35 (47.9%)
With PM extractions LJ+UJ	21 (65.6%)	13 (17.8%)
With PM extractions LJ	2 (6.3%)	6 (8.2%)
With PM extractions UJ	0	19 (26.0%)
Surgically assisted orthodontic treatment	**35 (44.3%)**	**35 (29.4%)**
MMD	4 (11.4%)	3 (9.1%)
SARME	23 (65.7%)	22 (66.7%)
Both	8 (22.9%)	8 (24.2%)
No treatment	**12 (10.6%)**	**11 (9.2%)**
Satisfaction		
Mean ± SD	3.98 ± 0.83 (n = 66)	3.67 ± 1.00 (n = 97)
Recommend (again) the applied treatment		
Yes	37 (56.1%)	32 (33%)
No	29 (43.9%)	65 (67%)
	66	97
Case 3 (n)	**72**	**107**
Treatment		
Orthodontic treatment	**18 (25%)**	**66 (61.7%)**
Without PM extractions	11 (61.1%)	45 (68.2)
With PM extractions LJ+UJ	2 (11.1%)	1 (1.5%)
With PM extractions LJ	1 (5.6%)	7 (10.6%)
With PM extractions UJ	4 (22.2%)	13 (19.7%)
Surgically assisted orthodontic treatment	**49 (68.1%)**	**35 (32.7%)**
MMD	0	2 (5.7%)

Table 1. Complete overview of the responses and results per case. (continued)

	OMFS (*n* = 379)	**ORTHO** (*n* = 303)
SARME	18 (36.7%)	14 (40%)
Both	31 (63.3%)	19 (54.3%)
No treatment	**5 (6.9%)**	**6 (5.6%)**
Satisfaction		
Mean ± SD	2.97 ± 1.14 (n = 66)	2.92 ± 1.17 (n = 97)
Recommend (again) the applied treatment		
Yes	21 (31.8%)	29 (29.9%)
No	45 (68.2%)	68 (70.1%)
	66	97
Technical aspects:		
Type of distractor MMD		
Tooth-borne	13 (59.1%)	5 (38.5%)
Bone-borne	7 (31.8%)	4 (30.8%)
Hybrid	2 (9.1%)	4 (30.8%)
Type of distractor SARME		
Tooth-borne	34 (68%)	50 (61.7%)
Bone-borne	10 (20%)	14 (17.3%)
Hybrid	6 (12%)	17 (21%)
Latency period MMD		
Direct	1 (4.5%)	0
0-5 days	5 (22.7%)	6 (46.2%)
5-7 days	13 (59.1%)	4 (30.8%)
7-10 days	3 (13.6%)	3 (23.1%)
Latency period SARME		
Direct	4 (8%)	14 (17.3%)
0-5 days	8 (16%)	31 (38.3%)
5-7 days	35 (70%)	27 (33.3%)
7-10 days	3 (6%)	9 (11.1%)
Distraction rate MMD		
0.25mm/day	4 (18.2%)	5 (38.5%)
0.5mm/day	14 (63.6%)	7 (53.8%)
1.0mm/day	4 (18.2%)	1 (7.7%)
2.0mm/day	-	-
Distraction rate SARME		
0.25mm/day	7 (14.3%)	18 (22.2%)
0.5mm/day	28 (57.1%)	56 (69.1%)
1.0mm/day	14 (28.6%)	7 (8.6%)
2.0mm/dag	-	-
Overcorrection MMD		

Table 1. Complete overview of the responses and results per case. (continued)

	OMFS (*n* = 379)	**ORTHO** (*n* = 303)
Yes	9 (42.9%)	3 (23.1%)
No	12 (57.1%)	10 (76.9%)
Overcorrection SARME		
Yes	34 (69.4%)	71 (87.7%)
No	15 (30.6%)	10 (12.3%)
Consolidation period MMD		
1 month	1 (4.8%)	1 (7.7%)
2 months	1 (4.8%)	2 (15.4%)
3 months	14 (61.9%)	3 (23.1%)
4 months	4 (19%)	5 (38.5%)
5 months	0	1 (7.7%)
6 months	2 (9.5%)	1 (7.7%)
Consolidation period SARME		
1 month	3 (6.1%)	0
2 months	2 (4.1%)	3 (3.8%)
3 months	28 (57.1%)	23 (28.8%)
4 months	7 (14.3%)	18 (22.5%)
5 months	0	4 (5.0%)
6 months	9 (18.4%)	32 (40%)
Discussion of orofacial soft tissue effects		
Yes	42 (70%)	58 (62.4%)
No	8 (13.3%)	22 (23.7%)
N/A	10 (16.7%)	13 (14%)
Total	**60**	**93**
Widening of the nose	36	48
Flattening of the upper lip	29	28
Downward displacement of the chin	4	7
Reduction of black buccal corridors	30	39

LJ, Premolar extractions in lower jaw; MMD, Mandibular Midline Distraction; OMFS, Oral and Maxillofacial Surgeons; N/A, Not applicable; ORTHO, Orthodontists; PM, Premolar; SARME, Surgically Assisted Rapid Maxillary Expansion; UJ, Premolar extractions in upper jaw.

Case 1

Case 1 was filled out completely by 135 ORTHO members (response rate of 44.6%), of which 118 members had chosen for orthodontic treatment with optional extractions, 10 members for surgically assisted orthodontic treatment (MMD, 0; SARME, 5; MMD and SARME, 5) and 7 members for no treatment. The mean score scale of satisfaction for our applied treatment was 3.5 ± 1.01 (*n* = 100), of which only 15 members (15.0%) would choose our applied treatment again.

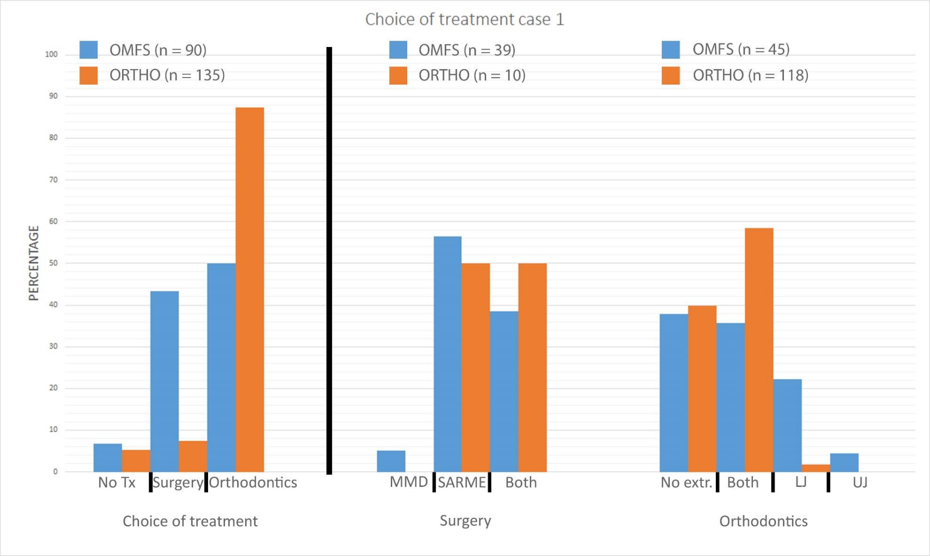

Fig. 1. Choice of treatment case 1.
LJ, Premolar extractions in lower jaw; MMD, Mandibular Midline Distraction; OMFS, Oral and Maxillofacial Surgeons; ORTHO, Orthodontists; SARME, Surgically Assisted Rapid Maxillary Expansion; Tx, Treatment; UJ, Premolar extractions in upper jaw.

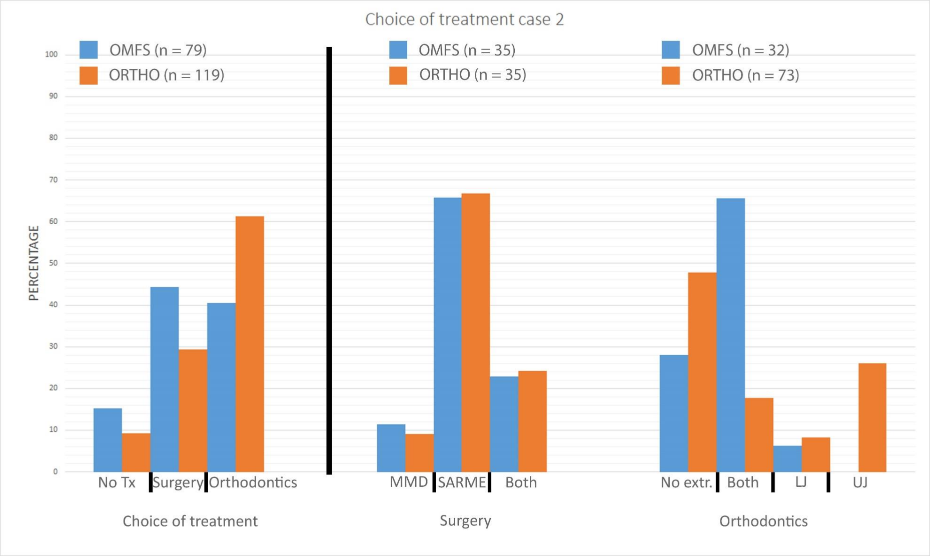

Fig. 2. Choice of treatment case 2.
LJ, Premolar extractions in lower jaw; MMD, Mandibular Midline Distraction; OMFS, Oral and Maxillofacial Surgeons; ORTHO, Orthodontists; SARME, Surgically Assisted Rapid Maxillary Expansion; Tx, Treatment; UJ, Premolar extractions in upper jaw.

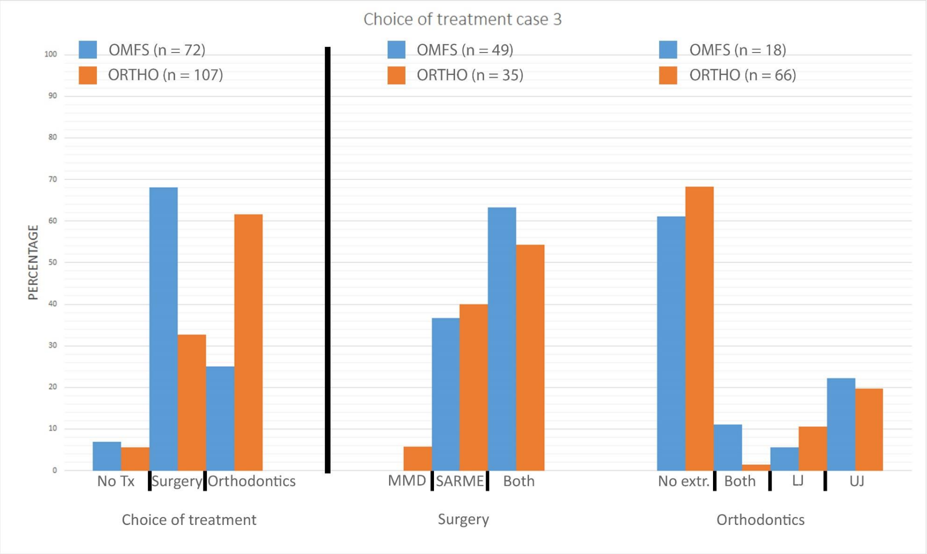

Fig. 3. Choice of treatment case 3.
LJ, Premolar extractions in lower jaw; MMD, Mandibular Midline Distraction; OMFS, Oral and Maxillofacial Surgeons; ORTHO, Orthodontists; SARME, Surgically Assisted Rapid Maxillary Expansion; Tx, Treatment; UJ, Premolar extractions in upper jaw.

On the other hand, 90 OMFS members (response rate of 23.7%) filled out completely, of which 45 members had chosen for orthodontic treatment with optional extractions, 39 members for surgically assisted orthodontic treatment (MMD, 2; SARME, 22; MMD and SARME, 15) and 6 members for no treatment. The mean score scale of satisfaction for our applied treatment was 3.67 ± 1.00 (*n* = 67), of which 27 members (40.3%) would choose our applied treatment again.

Case 2

Case 2 was filled out completely by 119 ORTHO members (response rate of 39.3%), of which 73 members had chosen for orthodontic treatment with optional extractions, 35 members for surgically assisted orthodontic treatment (MMD, 3; SARME, 22; MMD and SARME, 8) and 11 members for no treatment. The mean score scale of satisfaction for our applied treatment was 3.67 ± 1.00 (*n* = 97), of which 32 members (33%) would choose our applied treatment again.

79 OMFS members (response rate of 20.8%) filled out completely the same case. Out of this 32 members had chosen for orthodontic treatment with optional extractions, 35 members for surgically assisted orthodontic treatment (MMD, 4; SARME, 23; MMD and SARME, 8) and 12 members for no treatment. The mean score scale of satisfaction for our

applied treatment was 3.98 ± 0.83 (*n* = 66), of which 37 members (56.1%) would choose our applied treatment again.

Case 3

Case 3 was filled out completely by 107 ORTHO members (response rate of 35.3%), of which 66 members had chosen for orthodontic treatment with optional extractions, 35 members for surgically assisted orthodontic treatment (MMD, 2; SARME, 14; MMD and SARME, 19) and 6 members for no treatment. The mean score scale of satisfaction for our applied treatment was 2.92 ± 1.17 (*n* = 97), of which 29 members (29.9%) would choose our applied treatment again.

Finally, 72 OMFS members (response rate of 19%) filled out the same case completely, of which 18 members had chosen for orthodontic treatment with optional extractions, 49 members for surgically assisted orthodontic treatment (MMD, 0; SARME, 18; MMD and SARME, 31) and 5 members for no treatment. The mean score scale of satisfaction for our applied treatment was 2.97 ± 1.14 (*n* = 66), of which 21 members (31.8%) would choose our applied treatment again.

Technical aspects

See *Table 1* for a complete overview of the results per technical aspect. 93 ORTHO members (response rate of 30.7%) have performed at least one MMD and/or SARME annually. The general preference of distractor type was the tooth-borne distractor combined with a latency period of 0-5 days where after a distraction rate of 0.5mm/day was applied generally for both MMD and SARME. In contrast to SARME, generally no overcorrection of distraction is preferred for the MMD. Generally, after active distraction, a consolidation period of 4 months for MMD and 6 months for SARME is preferred. In general, before start of MMD and/or SARME possible orofacial soft tissue effects (widening of the nose, flattening of the upper lip, downward displacement of the chin and reduction of black buccal corridors) are discussed with the patients by 62.4% of the same 93 ORTHO members.

On the other hand, 60 OMFS members (response rate of 15.8%) have performed at least one MMD and/or SARME annually. The general preference of distractor type was the tooth-borne distractor combined with a latency period of 5-7 days where after a distraction rate of 0.5mm/day was applied generally for both MMD and SARME. During distraction generally no overcorrection is preferred for the MMD, but for SARME it is. After distraction generally a consolidation period of 3 months for both MMD and SARME is preferred. In general, before start of MMD and/or SARME possible orofacial soft tissue effects (widening of the nose, flattening of the upper lip, downward displacement of the chin and reduction of black buccal corridors) are discussed with the patients by 70.0% of the same 60 OMFS members.

Complications

Regarding complications, by the same 93 ORTHO and 60 OMFS members, 13 complications were reported for MMD (loose distractor, 2; discomfort, 3; non-union, 2; loss of tooth, 2; loss of vitality, 2; infection, 1 and severe laceration of soft tissue, 1) and 74 complications for SARME (bleeding, 5; loss of vitality, 5; loose distractor, 5; asymmetric expansion, 33; loss of tooth, 1; deviation of nasal septum, 1; gingival and periodontal recession and/or pockets, 6; necrosis of gingiva, 1; undesired expansion, 4; broken distractor, 2; floating maxilla, 1; bad split through periodontal ligament of central incisor, 1; severe relapse, 1; damage of central incisor apex, 1; too much resistance during distraction, 1; temporary change of incisor color, 1; temporary loose incisor, 1; sinusitis, 1; discomfort, 1; ankyloses of incisor, 1 and sensibility disturbance of the upper lip, 1).

DISCUSSION

In the orthodontic and oral and maxillofacial surgery literature, there are still a lot of controversies and a lack of consensus regarding indication for MMD and SARME, distractor type, latency period, distraction rate, overcorrection, and consolidation period for MMD and SARME. The main objective of this study was to provide an overview of the current practice for transverse mandibular and maxillary discrepancies in the Netherlands using a web-based survey about 3 specific cases. The results show that generally ORTHO prefer orthodontic treatment with optional extractions and OMFS lean towards surgically assisted orthodontic treatment. The choice for no treatment was for both specialisms broadly the same. Although the average satisfaction score per case for our applied treatments ranged between neutral and satisfied, our applied treatments seemed generally not to be preferred in the future by both specialisms. This might be related to the clinic where the clinicians were trained, but in the current survey the numbers were too low to draw any conclusions.

To our knowledge, in the literature this is the first survey regarding transverse mandibular and maxillary discrepancies with comparison from the view of ORTHO and OMFS. MacLaine et al. has previously conducted a nationwide survey in the United Kingdom for OMFS, however this was only focused on SARME[16]. MacLaine et al. showed a general preference for a tooth-borne distractor (78%) and a general preference of 5-7 days for latency period (roughly 50%)[16]. These preferences are in line with our results. However, the preference of distraction rate was 1mm/day with a preference of overcorrection by only 23%. These preferences are not in line with our general preference of distraction rate of 0.5mm/day and a strong preference for overcorrection.

In this study, there seems to be consensus on the technical aspects by both professions. The general preference of distractor type is the tooth-borne distractor with a distraction rate of 0.5mm/day for both MMD and SARME by both professions. ORTHO prefer a latency period of 0-5 days where OMFS prefer 5-7 days for both MMD and SARME. Finally, the consolidation period seems to be preferred 4 months for MMD and 6 months for SARME by ORTHO, where OMFS prefer 3 months for both MMD and SARME.

Regarding complications for MMD discomfort was mentioned most often. This could be related to the design of the distractor. Bone-borne distractors are positioned in the lower mucobuccal fold close to the mucosa of the lower lip, which could lead to pressure ulcers and discomfort. Due to the position of the bone-borne distractor and saliva with food accumulation, wound healing issues could occur. A second procedure, under local anesthesia or general anesthesia, is needed to remove the distractor. Moreover, tooth-borne distractors are positioned sublingual which could interfere with the tongue position and lead to discomfort. In this web-based survey, the mentioned complications are generally in line with our previous study on complications in MMD[17]. However, the reported 2 non-union cases are remarkable in this web-based survey.

Regarding complications for SARME, the most frequently mentioned complication was asymmetric expansion. A possible explanation for this could be the minimal invasive trend of surgery with transection of only the piriform aperture, the zygomatic buttress and the midpalatinal suture without transection of the pterygomaxillary junction. This theory is also supported with the outcomes of Carvalho et al. in the systematic review of complications for SARME. When transection of the pterygomaxillary junction was not performed there was an increased rate of asymmetric or incorrect and undesired expansion[18]. Due to the anatomic relation, the transection between the piriform aperture and the zygomatic buttress is never completely horizontal on both sides of the median osteotomy. Due to this, expanding the maxilla may result in an asymmetric position in vertical direction. Other factors that could lead to an asymmetric expansion are broken or malfunctioning distractors.

The most cited comment on the survey itself by the participants was the lack of patients' chief complaint per presented case. Only general information was given in order to make a clinical unbiased decision for treatment possible. However, in a clinical setting the preferences of the patient are essential to gain successful and satisfied outcomes within shared decision making. Another common cited comment was the lack of experiences with MMD and its clinical stability in the long-term. This lack of knowledge may have led to the non-surgical choice of orthodontic treatment for transverse mandibular discrepancies despite MMD is a proven surgical technique to widen the mandible with stable long-term outcomes[6,7].

CONCLUSIONS

In the Netherlands, generally, Orthodontists prefer orthodontic treatment with optional extractions and Oral and Maxillofacial Surgeons prefer surgically assisted orthodontic treatment for transverse mandibular and maxillary discrepancies. Regarding surgically assisted orthodontic treatment, MMD seems less preferred most likely due to lack of clinical experience or knowledge by both professions despite being a proven clinical surgical technique with stable long-term outcomes. Overall, there seems to be consensus on the technical aspects by both professions, except for the duration of the consolidation period. Regarding complications, encountered in daily practice in the Netherlands, for MMD and SARME these are mostly minor and manageable. Clinicians should be aware of a possible asymmetric or incorrect and undesired expansion following SARME and communicate this prior the treatment with their patients.

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Appendix I. *Case 1*, <u>before treatment</u>: **A1**, Clinical images; **B1**, Panoramic radiograph; **C1**, Lateral cephalogram; **D1**, Posterior-anterior cephalogram.

Appendix I. A1.

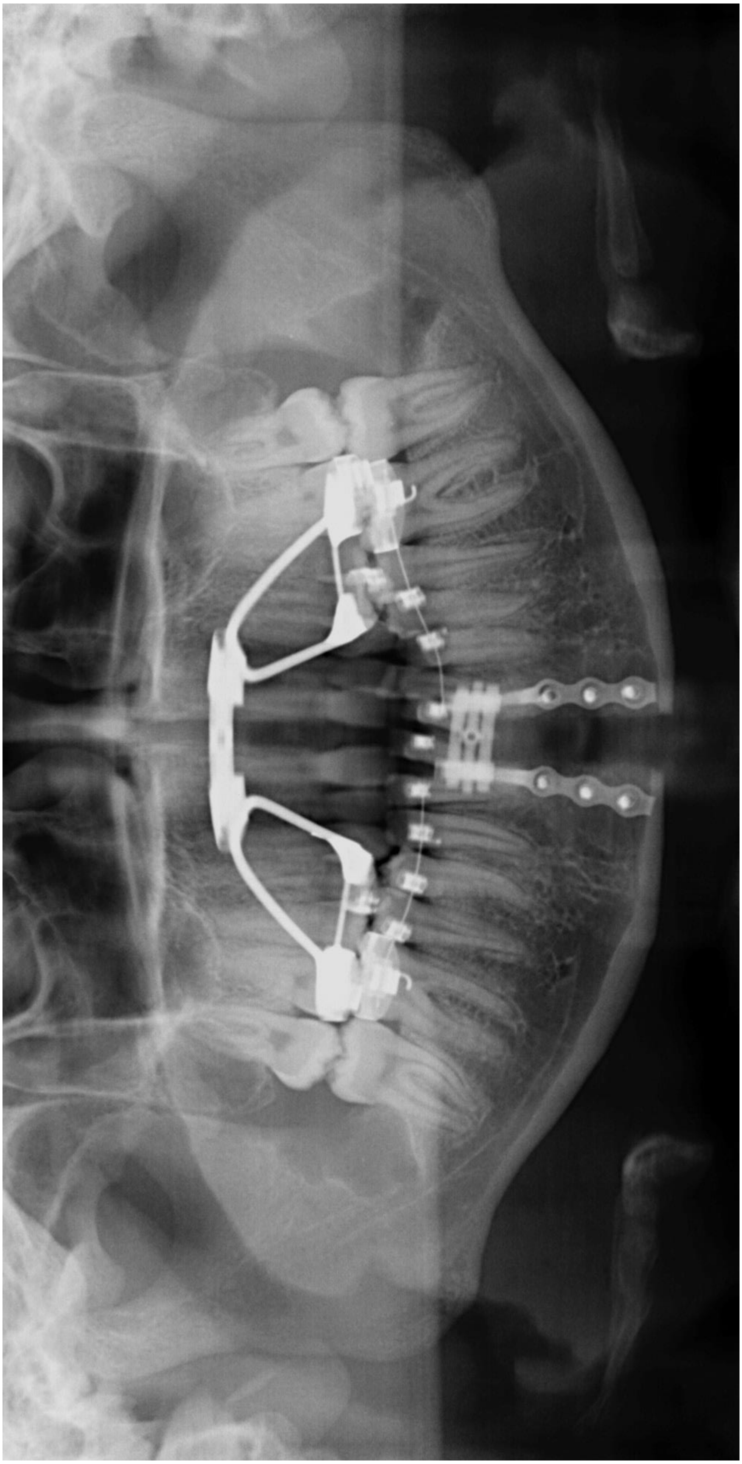
Appendix I. B1.

Appendix I. C1.

Appendix I. D1.

Appendix I. *Case 1*, during treatment: **A2**, Clinical images; **B2**, Panoramic radiograph.

Appendix I. A2.



Appendix I. B2.

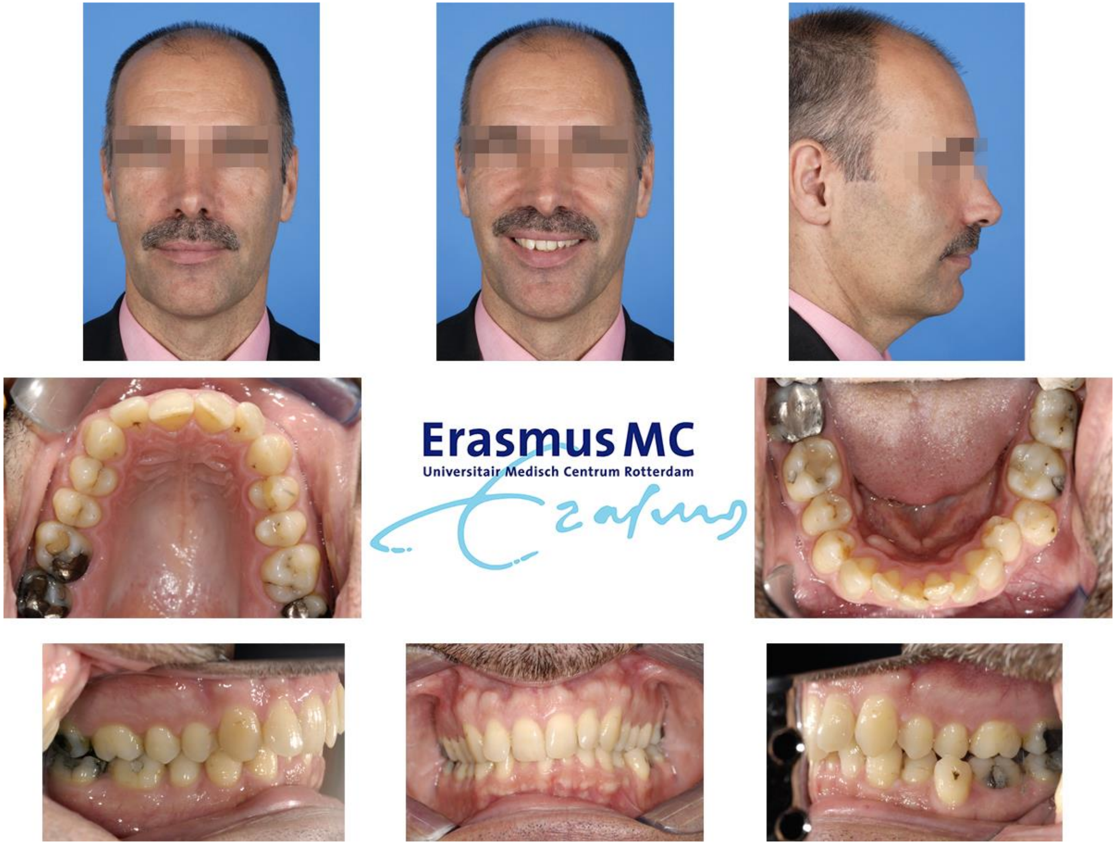
Appendix I. *Case 1*, <u>after treatment</u>: **A3**, Clinical images; **B3**, Panoramic radiograph; **C3**, Lateral cephalogram.

Appendix I. A3.

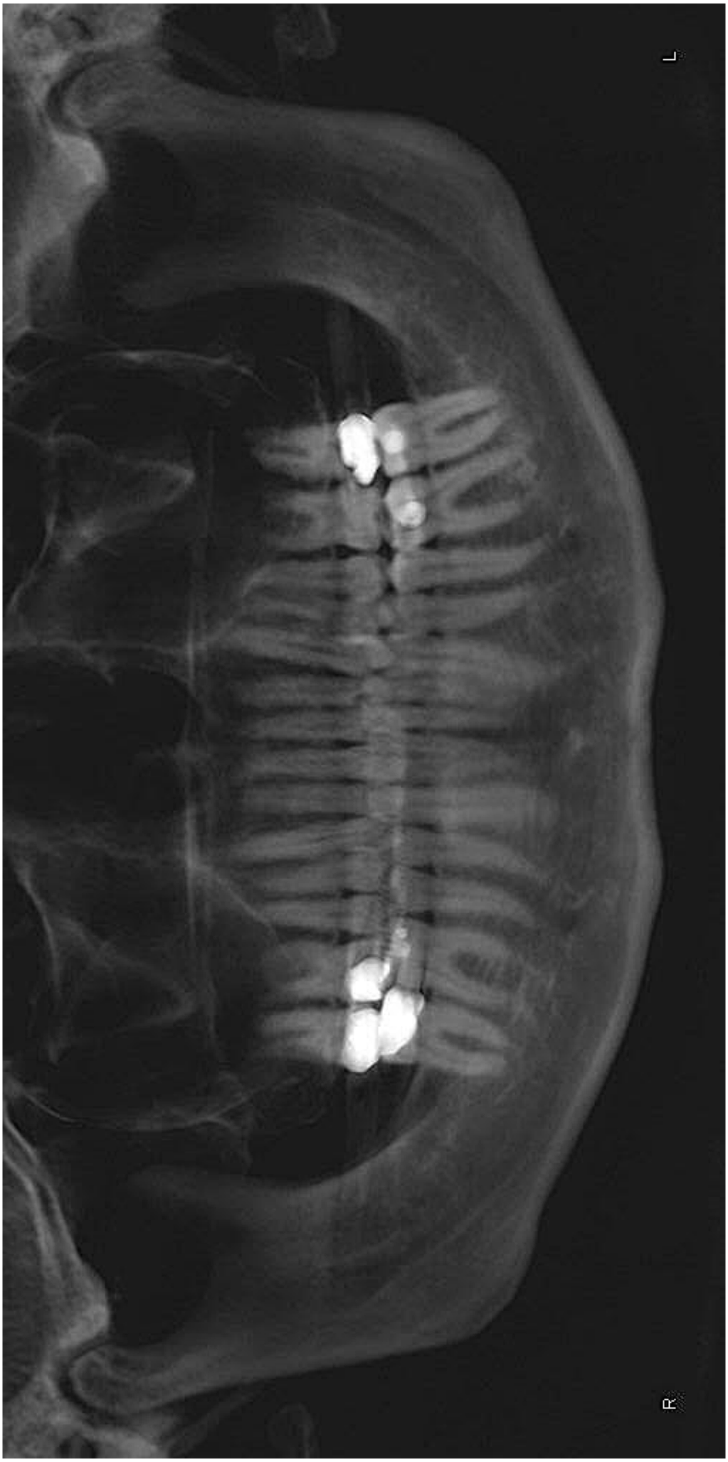
Appendix I. B3.

Appendix I. C3.

Appendix II. *Case 2*, before treatment: **A1**, Clinical images; **B1**, Panoramic radiograph; **C1**, Lateral cephalogram; **D1**, Posterior-anterior cephalogram.

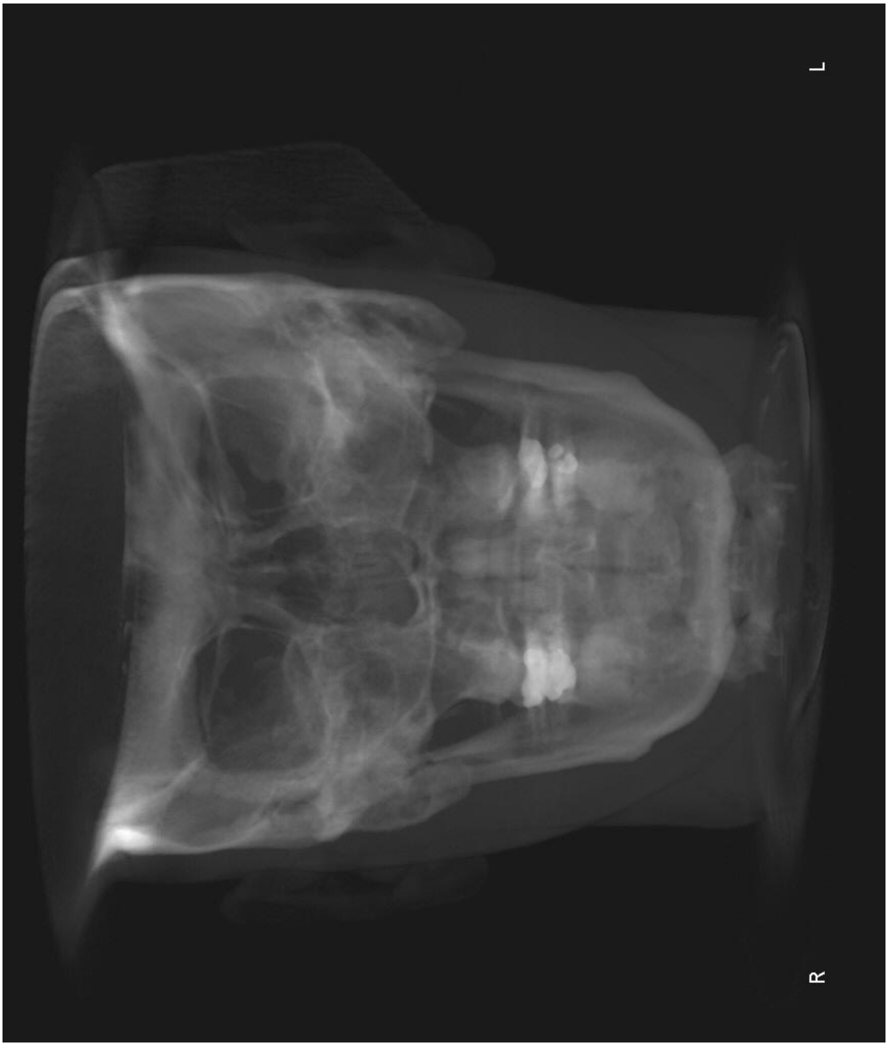


Appendix II. A1.



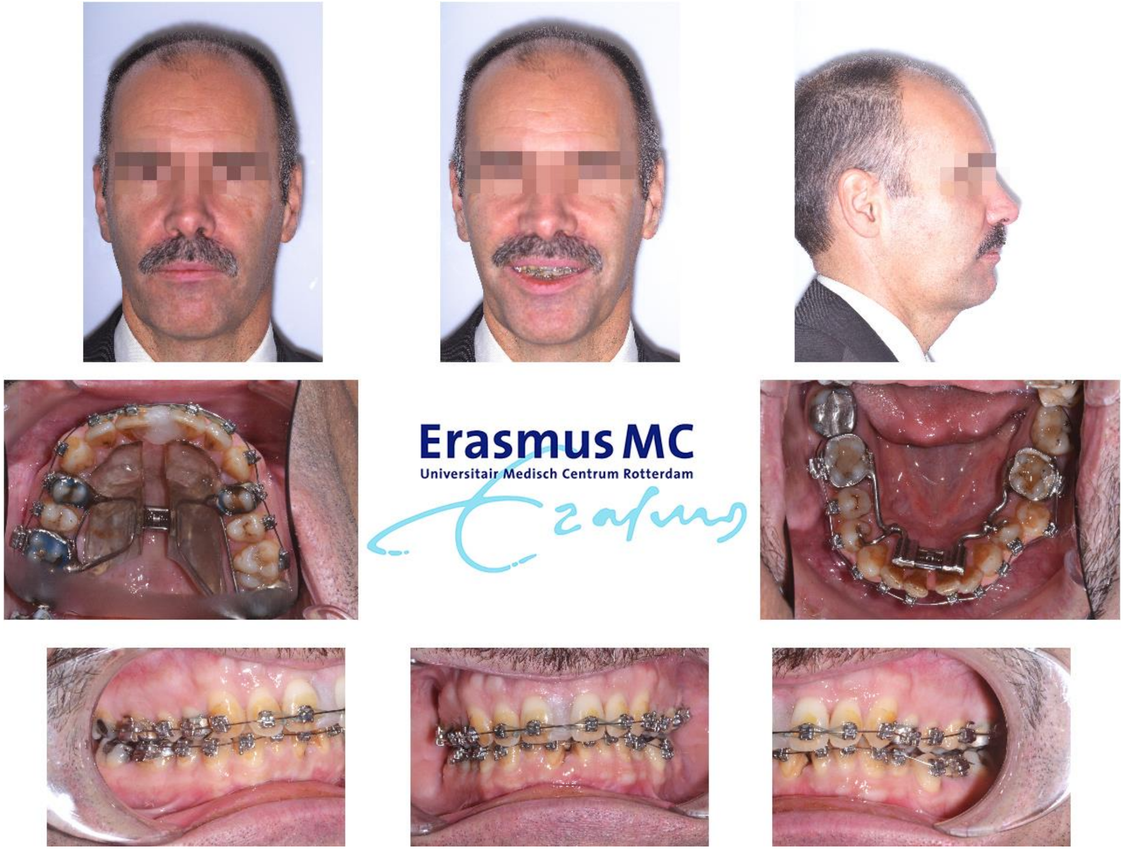
Appendix II. B1.

Appendix II. C1.



Appendix II. D1.

Appendix II. *Case 2*, during treatment: **A2**, Clinical images; **B2**, Panoramic radiograph.



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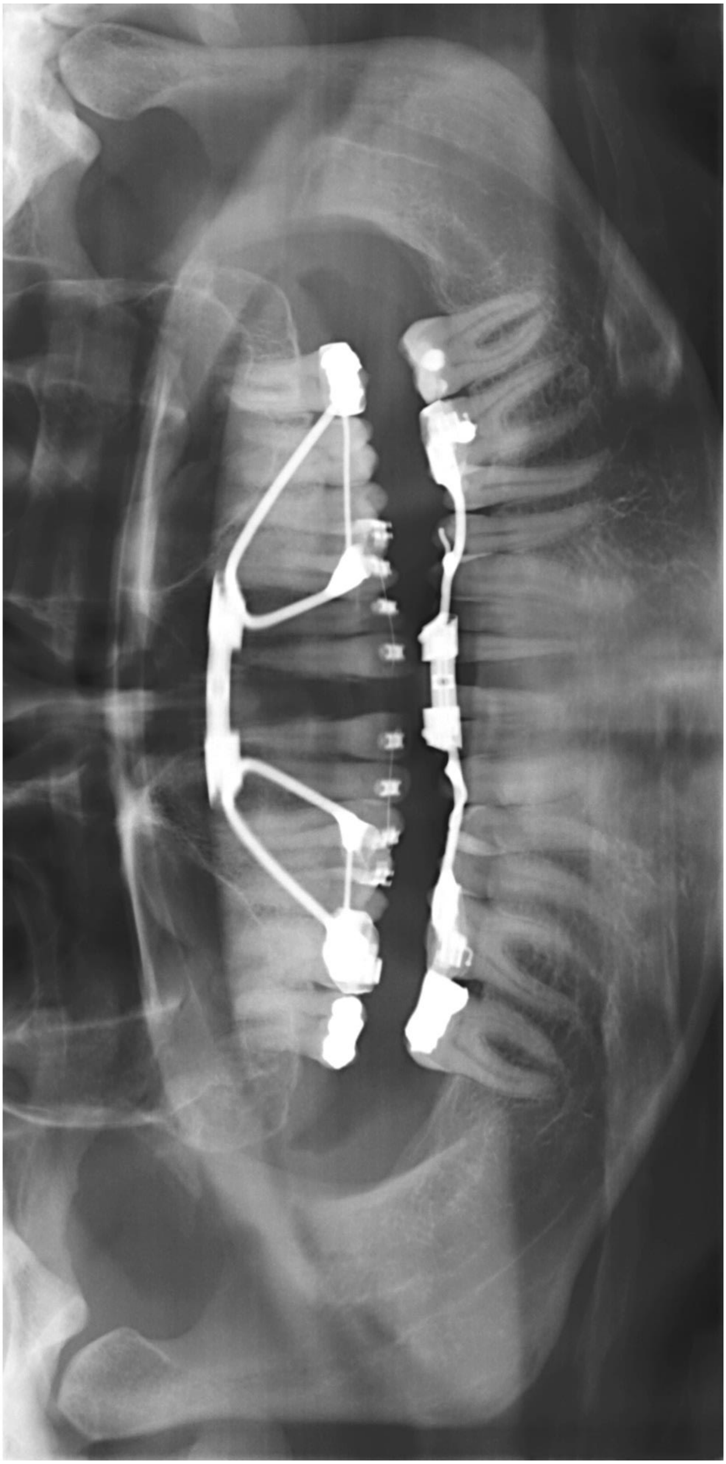
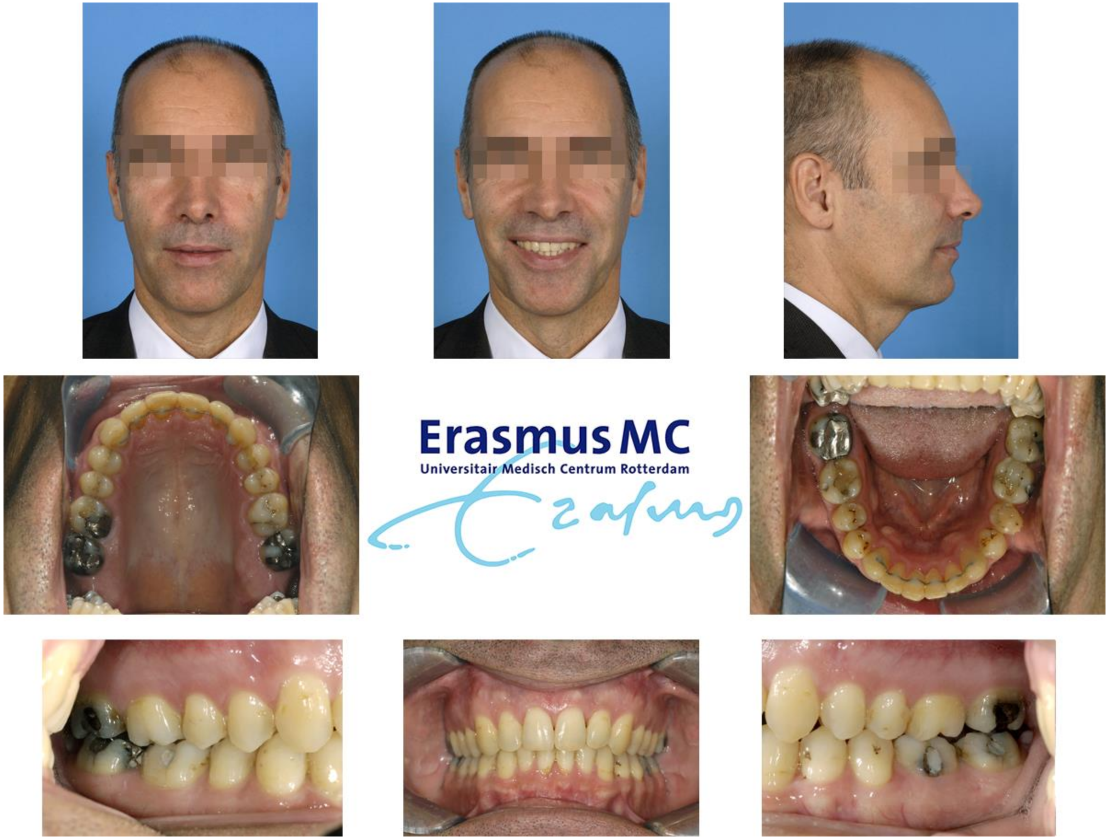
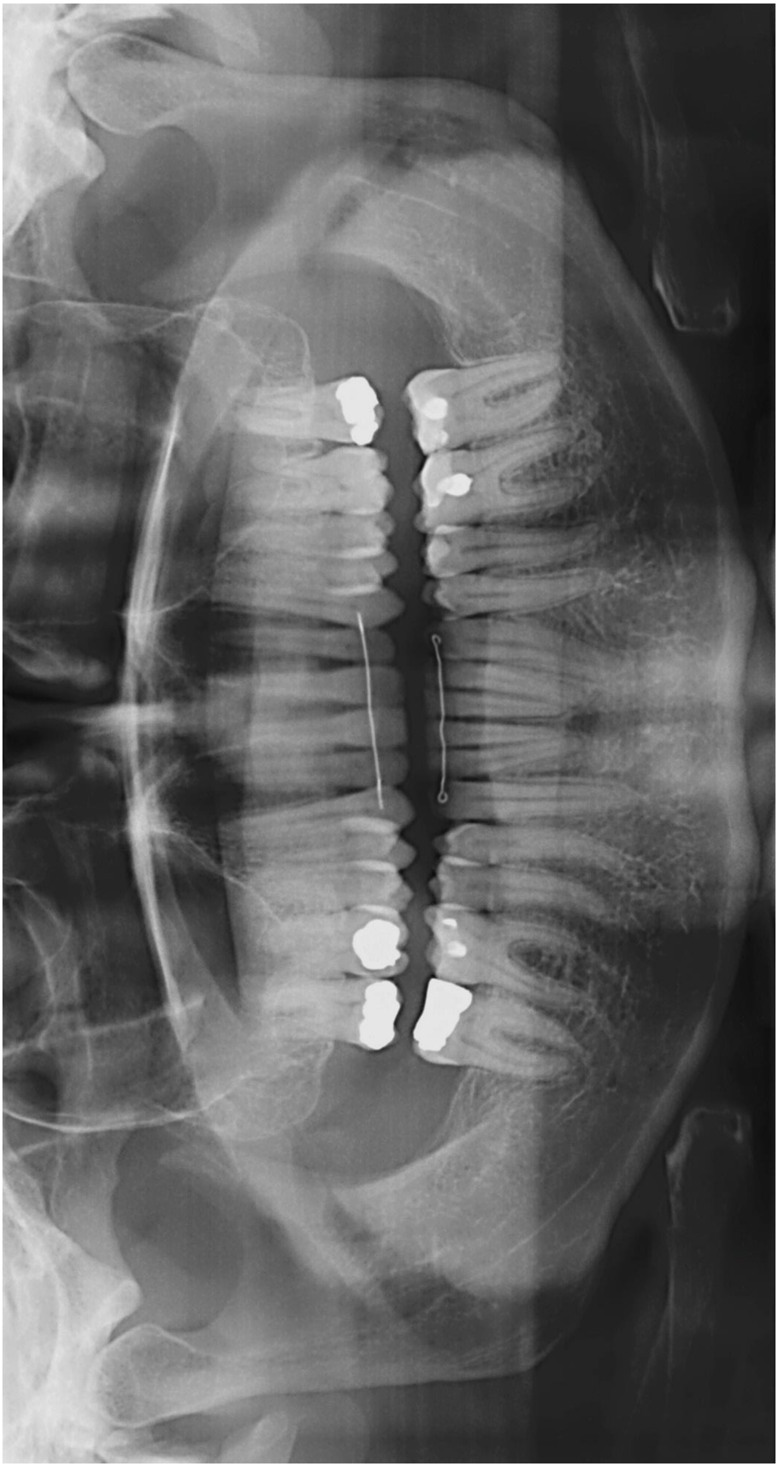


Appendix II. B2.

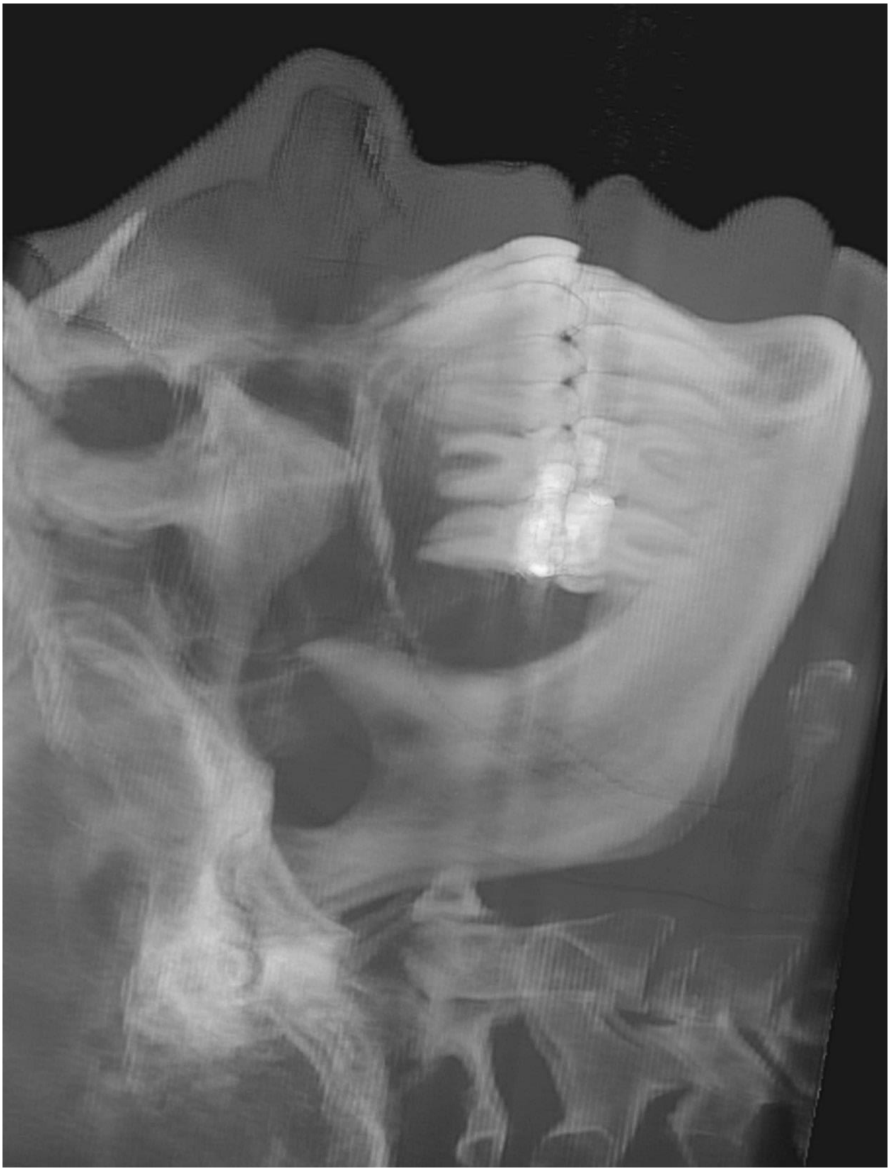
Appendix II. *Case 2*, after treatment: **A3**, Clinical images; **B3**, Panoramic radiograph; **C3**, Lateral cephalogram.



Appendix II. A3.



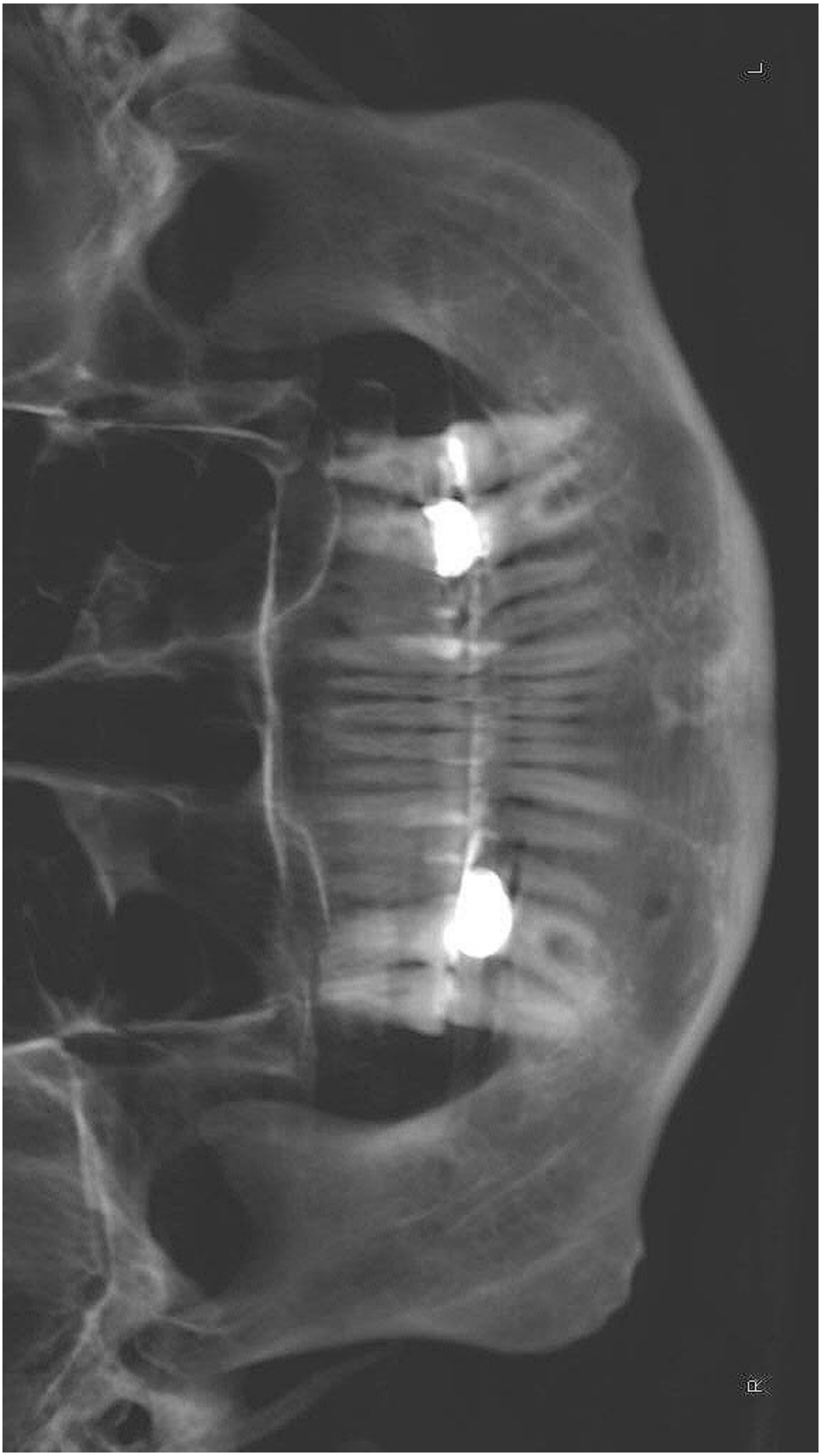
Appendix II. B3.



Appendix II. C3.

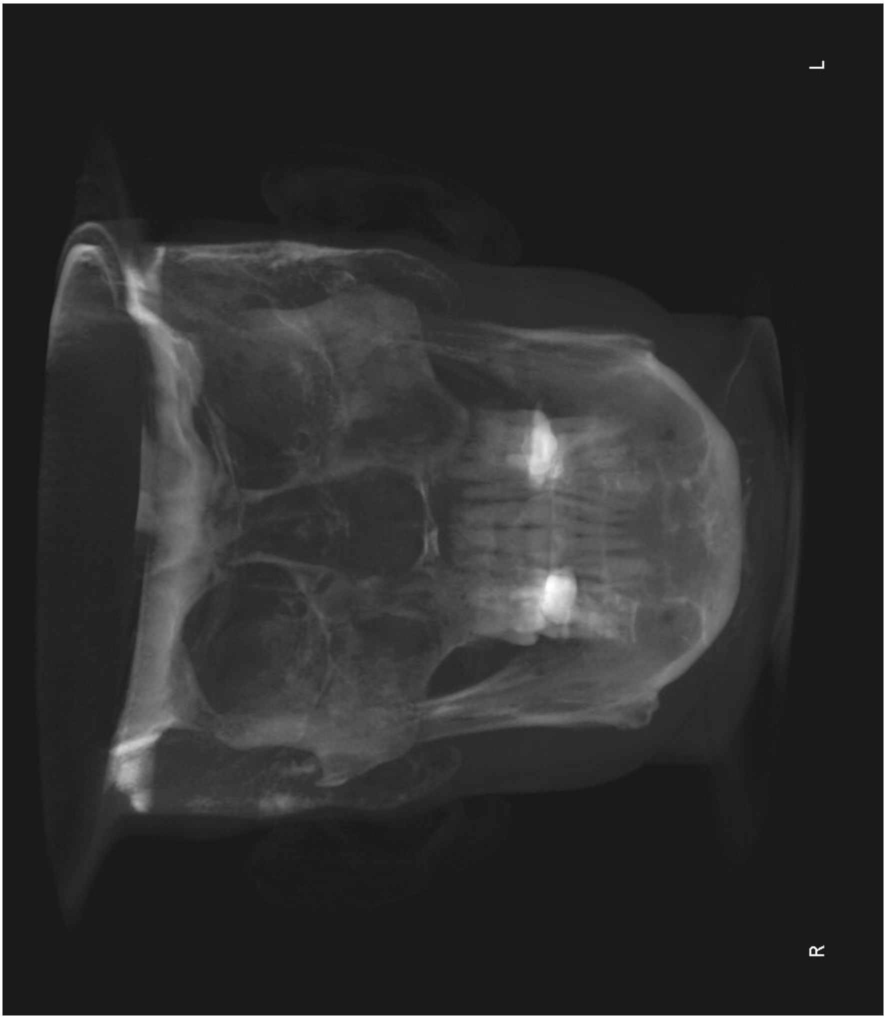
Appendix III. *Case 3*, before treatment: **A1**, Clinical images; **B1**, Panoramic radiograph; **C1**, Lateral cephalogram; **D1**, Posterior-anterior cephalogram.

Appendix III. A1.



Appendix III. B1.

Appendix III. C1.



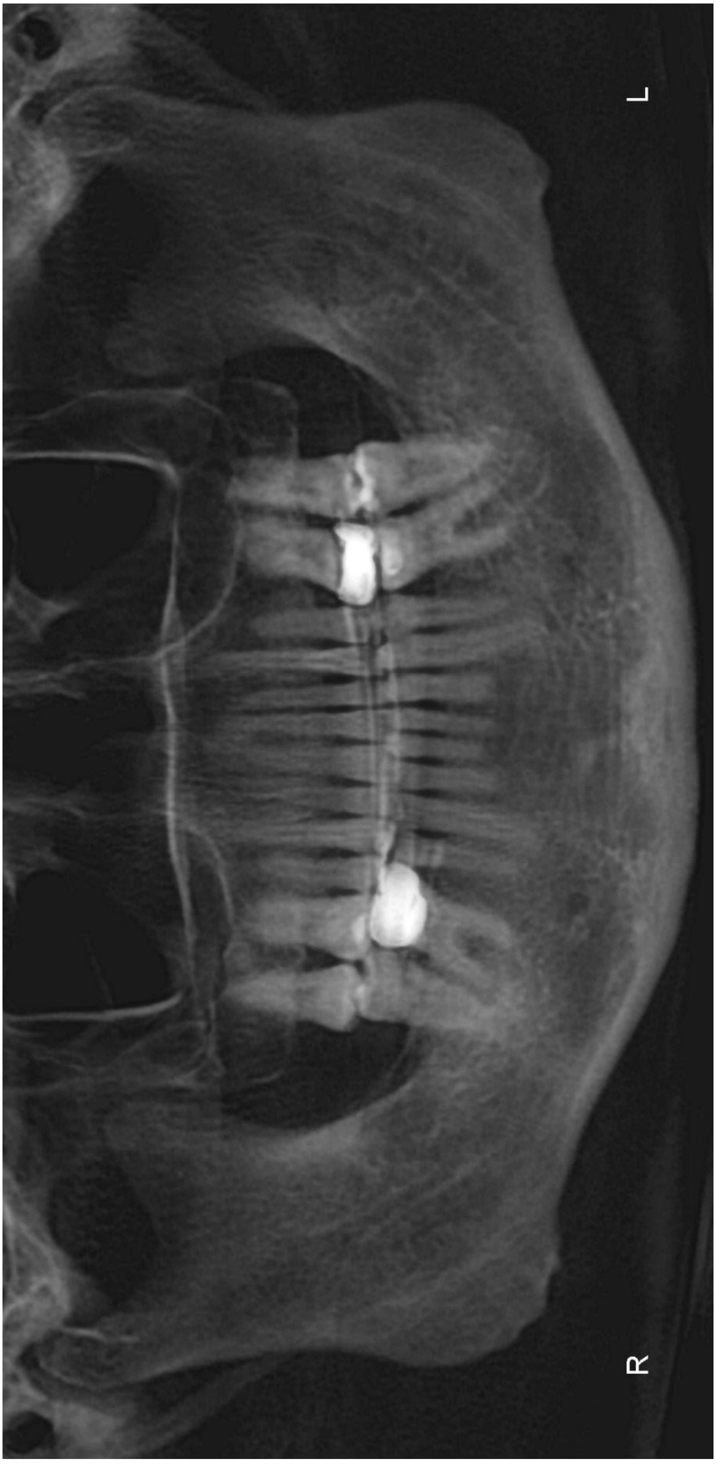
Appendix III. D1.

Appendix III. *Case 3*, during treatment: **A2**, Clinical images.

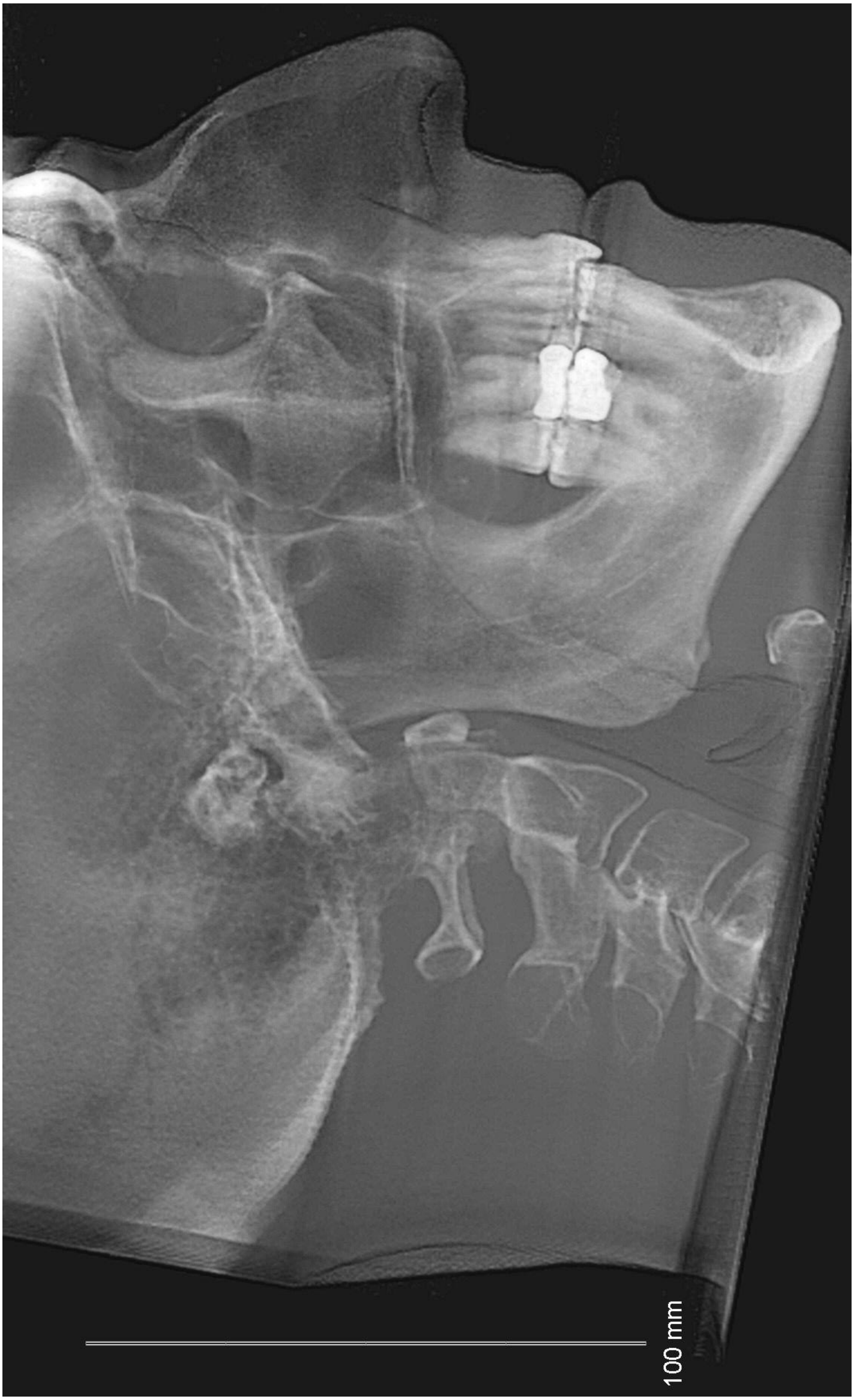
Appendix III. A2.

Appendix III. *Case 3*, after treatment: **A3**, Clinical images; **B3**, Panoramic radiograph; **C3**, Lateral cephalogram.

Appendix III. A3.



Appendix III. B3.



Appendix III. C3.

10

Complications in Mandibular Midline Distraction

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ABSTRACT

Mandibular midline distraction (MMD) is a relatively new surgical technique for correction of transverse discrepancies of the mandible. This study assesses the amount and burden of complications in MMD. A retrospective cohort study was performed on patients who underwent MMD between 2002 and 2014. Patients with congenital deformities or a history of radiation therapy in the area of interest were excluded. Patient records were obtained and individually assessed for any complications. Complications were graded using the Clavien-Dindo classification system. 73 patients were included of which 33 were male and 40 were female. The mean follow-up was 2.1 years. 29 patients had minor complications, grade I and II. 2 patients had a grade IIIa and 3 patients had a grade IIIb complication. Common complications were pressure ulcers, dehiscence and (transient) sensory disturbances of the mental nerve. This study shows that although, MMD is a relatively safe method, complications can occur. Mostly the complications are mild, transient and manageable without the need for any re-operation.

INTRODUCTION

In the 1990s a surgical technique to widen the mandible called mandibular midline distraction (MMD) was introduced. The indications for the procedure include anterior and posterior crowding and a uni- or bilateral crossbite.

The technique comprises a vertical osteotomy which is placed in the anterior mandible, preferably in the midline. A tooth-borne, bone-borne or hybrid distractor is applied during or before surgery depending on the type of distractor. After a latency period of approximately 1 week, the distractor is activated until the desired widening is achieved. A period of 2-3 months of rest ensures consolidation of the two hemi-mandibles.

To adequately inform a patient before a combined orthodontic and surgical treatment, it is necessary not only to tell them about the effectiveness but also the risks. Since the introduction of MMD, research focused largely on the biomechanical effectiveness of the technique. These studies show stable results of the treatment over time, with little relapse[1,2]. Less attention was aimed at the amount and impact of complications that can occur during the surgery and distraction period. Von Bremen et al. presented a comprehensive study on the complications in the first two weeks after MMD using a tooth-borne distractor[3]. Mommaerts et al. studied the morbidity of MMD using the success criteria for craniofacial distraction osteogenesis as proposed by the steering group of European Collaboration on Cranial Facial Anomalies[4]. These studies are either limited in their follow-up period or include a relatively small number of patients. Therefore, the aim of this study was to assess the number of complications using MMD in a comprehensive patient cohort with a long follow-up period.

MATERIALS AND METHODS

This study was conducted with following approval of the Standing Committee on Ethical Research in Humans of the Erasmus MC, University Medical Center Rotterdam, the Netherlands (MEC 2013-367). A retrospective cohort study was performed. Inclusion criteria were: transverse mandibular discrepancy, treated with MMD and at least 16 years of age. Exclusion criteria were: Congenital craniofacial deformity patients and history of radiation therapy in the area of interest.

The surgical technique used was similar to that described by Mommaerts et al[5]. When a tooth-borne distractor was used an orthodontist pre-operatively placed the distractor. All patients who underwent MMD in the Erasmus MC, University Medical Center

Rotterdam, the Netherlands, between 2002 and 2014 and fulfilled the inclusion criteria were included. The medical records were obtained and hand searched for complications during the surgical procedure and follow-up period.

The Clavien-Dindo Classification was applied to grade the severity of the complications (*Table 1*)[6]. Furthermore, the (transient) adverse outcomes were categorized. Grade I and II are considered as minor complications and from grade IIIa onwards as major.

Table 1. Clavien-Dindo Classification.

Grades	Definition
Grade I:	Any deviation from the normal postoperative course without the need for pharmacological treatment or surgical, endoscopic and radiological interventions.
	Allowed therapeutic regimens are: drugs as antiemetics, antipyretics, analgetics, diuretics and electrolytes and physiotherapy. This grade also includes wound infections opened at the bedside.
Grade II:	Requiring pharmacological treatment with drugs other than such allowed for grade I complications. Blood transfusions and total parenteral nutrition are also included.
Grade III:	Requiring surgical, endoscopic or radiological intervention
Grade III-a:	intervention not under general anesthesia
Grade III-b:	intervention under general anesthesia
Grade IV:	Life-threatening complication (including CNS complications)* requiring IC/ICU-management
Grade IV-a:	single organ dysfunction (including dialysis)
Grade IV-b:	multi organ dysfunction
Grade V:	Death of a patient
Suffix 'd':	If the patients suffers from a complication at the time of discharge, the suffix "d" (for 'disability') is added to the respective grade of complication. This label indicates the need for a follow-up to fully evaluate the complication.

*Brain hemorrhage, ischemic stroke, subarrachnoidal bleeding, but excluding transient ischemic attacks (TIA); CNS, central nervous system; IC, intermediate care; ICU, intensive care unit

RESULTS

In total 73 patients were included, 33 males and 40 females (*Table 2*). The mean age at the time of surgery was 29 years and the mean follow-up time was 2.1 years. 64 were treated with a bone-borne distractor and 9 with a tooth-borne distractor. 62 patients also underwent simultaneous surgically assisted rapid maxillary expansion (SARME), mostly during a bimaxillary expansion (BiMEx) procedure. After the initial widening procedures, the following orthognathic surgeries were performed: bilateral sagittal split osteotomy, LeFort I osteotomy, segment osteotomy and genioplasty.

Table 2. Patient characteristics.

Number of patients	73
Mean age	29
Follow-up	Mean: 2.1 years Range: 0.3-6.3 years Standard deviation: 1.4
Sex distribution	Male: 33 Female: 40
Distractor	Bone-borne: 64 Tooth-borne: 9
Consecutive orthognathic surgery	Surgically Assisted Rapid Maxillary Expansion: 62 Bilateral Sagittal Split Osteotomy: 30 LeFort 1: 18 Segmental osteotomy: 1 Genioplasty: 2

Complications that occurred included wound dehiscence, pressure ulcers, extraction of teeth and reoperations (*Table 3 and 4*). Consequently, the Clavien-Dindo grade ranged from I to IIIb. Included in group I (37%) were: wound dehiscence (13.7%), pressure ulcers (12.3%), (transient) sensory deficits (11%) and (transient) temporomandibular joint complaints (6.8%). The (transient) sensory deficiencies included hypo- and paraesthesia of the mental nerve as described in the patient records. The (transient) temporomandibular joint complaints included transient joint tenderness and clicking of the joint. Grade I also included some distractor related complications. In one patient the distracter bent at the end of the distraction period (**Fig. 1**). Enough widening was achieved; however, the distraction gap was V-shaped. Another patient was activating the distractor in the wrong direction. Fortunately, it was observed on time and could be reversed. A grade II (2.7%) was scored in two patients who needed antibiotic treatment: in one case as a result of wound infection, in the other as a result of severe gingivitis. In the latter case the patient was too afraid to brush her teeth after the procedure. The IIIa grade (2.7%) was scored when a patient needed extractions of 2 teeth following periodontal decay after MMD and a second patient needed release of mucosal adhesions which emerged after MMD. The three patients who scored a grade IIIb complication (4.1%) needed a second surgical procedure under general anaesthesia. In the first patient, the distractor type was too small to obtain adequate expansion of the mandible and a second procedure with a larger distractor was necessary. A second patient required remodelling of the chin because of a palpable distraction gap, which was corrected during the already planned bilateral sagittal split osteotomy procedure. A third patient suffered from an insufficient expanding distractor and a new distractor needed to be placed to achieve enough widening.

Table 3. Complications.

Clavien-Dindo classification				
Grade	**I**	**II**	**IIIa**	**IIIb**
Patients (%)	27 (37%)	2 (2.7%)	2 (2.7%)	3 (4.1%)

Table 4. Number of complications.

	Pressure ulcer	**Dehiscence**	**TMJ related**	**Sensory disturbances**	**Distractor related failure**	**Tooth extraction**
Patients (%)	9 (12.3%)	10 (13.7%)	5 (6.8%)	8 (11%)	4 (5.5%)	1 (1.4%)

Fig. 1. Bended distractor and v-shaped distraction gap.

DISCUSSION

MMD, a relatively new technique, is considered a relatively safe method to widen the mandible[7]. This study confirms this opinion, with only 5 major complications (CDS grade IIIa and IIIb, 6.8%) and no mortalities or life-threatening complications in 73 patients. The most common complications in MMD are wound dehiscence and pressure ulcers and although uncomfortable for the patient an antibiotic regime was required to overcome an infection as result of wound dehiscence in only one instance.

The most serious complications were related to the distractor, either due to technical problems or usage of the distractor. Therefore, clear instructions on how to activate the distractor and strict follow-up are important factors to prevent distractor related complications. In addition, when a patient is not able to reliably activate the distractor, due to physical disability or anxiety, family or relatives could be instructed to use the distractor.

In this study mostly bone-borne distractors were used. The bulk of the bone-borne distractor is positioned close to the mucosa of the lower lip and this probably accounts for most of the pressure ulcers. The relatively high amount of wound dehiscence might be attributable to the position of the incision in the mucobuccal fold. Firstly, this location of the incision ensures saliva and food accumulation in the wound and secondly the labial fold is continuously moving which could compromise the healing process. Since all surgeries took place in a teaching hospital the complication rate could be a little higher than in a normal setting. Although every surgical intervention is performed under supervision it cannot always prevent less skilled surgical techniques.

Many of the registered complications were related to the position of the bone-borne distractor, and although complications were mostly transient, they were still uncomfortable for the patients. A second procedure is always necessary to remove a bone-borne distractor. Therefore, at the end of the follow-up period, having used multiple variants of the bone-borne distractor types, a shift towards the use of tooth-borne distractors took place in our clinic. However, the effect of this shift on the amount and burden of the complications has not been evaluated yet .

The risk of acquiring a temporomandibular joint disorders following MMD, might cause orthodontists and maxillofacial surgeons to hesitate to indicate MMD. This study shows that only 5 patients had transient joint complains, which was expressed in joint clicking and joint tenderness. In this study patients were not systematically assessed on temporomandibular joint disorders (TMD). More in vivo research on the effect of MMD on developing TMD and joint remodelling, preferably with state of the art imaging techniques is necessary. Post-operative sensory disturbances were seen in 11% of the patients and while occurring in the minority of the patients in a transient fashion, this can be quite aggravating.

In surgery, complications can occur due to numerous factors such as age, comorbidity, medical appliances used and surgeons' experience. In addition, different surgical procedures have various complication rates depending on complexity and proximity of critical tissues. Traditionally, in oral and maxillofacial literature, the main focus in research on surgical therapies, has been describing the biomechanical and technical outcome of these therapies. Nowadays, an increase of research on patient's experience and related outcomes, such as complications and cost effectiveness of therapies, is reported.

When systematically evaluating complications, the use of a standardized grading system minimizes the subjective assessment of an observer. Furthermore, a grading system enables the comparison of complications with other studies. In general surgery, the Clavien-Dindo classification system (CDS) was created to systematically grade complications[6]. After revising the system in 2004, wide acceptance in the general surgical literature was obtained. In the oral and maxillofacial surgery, the use of CDS is limited to a few articles in the field of head and neck surgery[8-11]. To our knowledge this is the first time CDS is used to assess complications in orthognathic surgery.

This study was conducted with a retrospective design and therefore results are limited by the reports in the medical records. A prospective trial systematically examining patients could overcome these uncertainties. These studies should include patients' questionnaires directed towards discomfort, pain, satisfaction and monitoring of clinical outcome and complications.

CONCLUSION

It is essential for caregivers to fully inform a patient about a chosen treatment including expected discomfort, pain and frequently occurring complications. Though MMD with bone-borne distractors was found to be a relatively safe method to widen the mandible, complications did occur. Fortunately, mostly the complications were mild, transient and manageable, without the need for any re-operation. Future prospective studies on MMD including the use of tooth-borne distractors should clarify whether these cause less discomfort, pain and fewer complications then the bone-borne devices.

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V

GENERAL DISCUSSION, LIMITATIONS, FUTURE PERSPECTIVES AND CONCLUSIONS

GENERAL DISCUSSION

Mandibular Midline Distraction (MMD) and Surgically Assisted Rapid Maxillary Expansion (SARME) are effective and accepted surgical treatments to correct respectively mandibular and maxillary discrepancies[1,2].

The objectives of the work presented in the general introduction of this thesis were to study:

- Three-dimensional (3D) dento-skeletal effects of bone-borne versus tooth-borne MMD and tooth-borne-SARME.
- 3D soft tissue effects of MMD and SARME.
- Long-term dento-skeletal effects of bone-borne MMD and tooth-borne SARME.
- Patient experience and satisfaction of MMD and SARME.
- Current practice of transverse mandibular and maxillary discrepancies among orthodontists and oral and maxillofacial surgeons in the Netherlands.
- Complications with MMD.

All findings from the studies performed will be discussed separately in a broader perspective using the knowledge obtained from current literature.

3D dento-skeletal effects of bone-borne versus tooth-borne MMD and tooth-borne SARME

Regarding the finite element method (FEM) studies presented in our systematic review in **Part I**, *Chapter 2*, bone-borne MMD applies distraction forces more anteriorly at basal bone level whereas tooth-borne MMD applies distraction forces more posterolateral due to the anchorage on the (pre)molars[3-6]. The biomechanical effects of the different type distractors may influence the distraction outcome and have their influence on the temporomandibular joint (TMJ)[7-9]. Until now research on dento-skeletal effects of MMD using 3D imaging analysis techniques has been reported scarcely[10-12], and is largely performed using conventional methods like dental casts and posterior-anterior cephalograms[13-17]. In contrast, SARME is well studied using 3D imaging analysis techniques[18-25]. In contrast, only one study reported on dento-skeletal effects after bimaxillary expansion (BiMEx) using 3D imaging analysis techniques[26]. However, to our knowledge there has been no clinical study performed comparing the dento-skeletal effects of bone-borne versus tooth-borne MMD using 3D imaging analysis techniques. For this reason, in **Part II**, we evaluated the 3D dento-skeletal effects of bone-borne versus tooth-borne MMD and tooth-borne-SARME in *Chapter 4*. In this retrospective observational study, 30 patients fulfilled the inclusion criteria. All 30 patients had undergone MMD, of whom 20 patients with a bone-borne MMD and 10 patients with a tooth-borne MMD using the same surgical technique. All 20 bone-borne MMD patients and 8 out of 10 tooth-borne MMD patients had undergone simultaneously tooth-borne SARME. Measurements were performed using cone beam computed tomography (CBCT) records taken pre-operatively (T1), immediately post-distraction (T2), and 1 year post-operatively (T3). The results showed stable dento-skeletal effects of bone-borne and tooth-borne MMD and tooth-borne SARME after 1 year, proving them to be reliable treatment options for transverse mandibular and maxillary discrepancies. All interdental distances were significantly increased pre-operatively versus immediately post-distraction and pre-operatively versus 1 year post-operative timepoint regarding the bone-borne MMD. The applied forces with the bone-borne distractor are at basal bone level resulting in no significant tipping of the (first) premolar at 1 year post-operative which indicate a more parallel expansion of the (first) premolars on both tip and apex level. This outcome is in line with the skeletal effects of the bone-borne MMD regarding a more parallel distraction gap at immediately post-distraction. In addition, no significant changes were seen in ramal angle and inter condylar distance for bone-borne MMD. 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[26]. In contrast, Landes et al. observed a significant decrease in inter condylar distance for bone-borne MMD[11]. This outcome should however be interpreted carefully given the low number of patients (n=9) included. In the same study, condylar angulation and vertical medial, cranial, and lateral distances to the fossa remain unchanged[11]. This is in contrast to our study as we observed significant increase in intercondylar axes for bone-borne MMD at 1 year post-operative, which is indicating a condylar exorotation in the axial plane.

On the other hand, the canine and (anchorage) first premolar showed significant tipping for tooth-borne MMD. Immediately post-distraction evaluation showed a V-shape distraction gap and thus anterior mandibular skeletal tipping in the coronal plane suggesting dento-skeletal tipping of the mandibular canine and first premolar for tooth-borne MMD. There were no significant changes seen in ramal angle and inter condylar distance. These results are broadly in line with Seeberger et al.[10], as they observed significant tipping of the mandibular corpus without change of intercondylar distance. In addition they found significant tipping of the (first) premolar due to the anchorage and distraction forces of the tooth-borne distractor. In contrast to our results, significant tipping of the (first) molar was seen also in their study. It should be noted that their results were obtained 3 months after surgery and before orthodontic treatment which makes a comparison difficult.

For tooth-borne SARME (anchorage) the first premolar showed significant tipping when combined with bone-borne and tooth-borne MMD both. Theoretically, tooth-borne distractors for SARME perform their distraction forces on dento-alveolar level and bone-borne distractors at higher position in the palatal vault. After performing osteotomies, the maxilla is still connected to the skull base and during expansion there is resistance at midpalatal suture level. Moreover, in our included cases no pterygomaxillary disjunction was performed. Therefore, during expansion the resistance is located at cranial level (midpalatal suture) and posterior (pterygomaxillary junction) for both tooth- and bone-borne distractors. The results showed significant increase in piriform aperture base width and piriform aperture lateral width at pre-operative versus immediately post-distraction. However, at 1 year post-operative only piriform aperture base width remained significantly increased when combined with bone-borne MMD. This outcome is in concordance with the outcomes of Seeberger et al. and Zandi et al. for tooth-borne SARME[22,25], and indicates a (reverse) V-shape widening of the nasal floor in the coronal plane (skeletal tipping). In addition, Zandi et al. did not find any significant difference in skeletal tipping for bone-borne versus tooth-borne SARME[22].

3D soft tissue effects of MMD and SARME

From a clinical perspective, it is relevant to know how the presented dento-skeletal effects can affect the overlying soft tissue in the orofacial area for patients following MMD and SARME.

In **Part II**, the 3D soft tissue effects of MMD and SARME are described in *Chapter 5*. In this retrospective observational study, we performed an automatic stereophotogrammetry landmarking analysis in 20 patients. All 20 patients had undergone tooth-borne SARME. Twelve of these patients had undergone BiMEx, all of which underwent a bone-borne MMD. Stereophotogrammetry records at pre-operative and 1 year post-operative were analysed with an automatic 3D facial landmarking algorithm using 2D Gabor wavelets as described by De Jong et al.[27,28]. The results showed a downward displacement of the soft tissue pogonion with a tendency towards an increase in the inter-soft tissue gonion distance. Furthermore, a transversal widening of the inter alar width and a tendency for an increase of the inter alar curvature point width were observed. These results are similar to what has been described by Bianchi et al.[26]. In their study, a forward and downward displacement of the chin was observed with a forward projection of the lower lip[26]. It should be noted that SARME was performed simultaneously in their study and in our study. Regarding the downward displacement of the soft tissue pogonion, we think this is the effect of the maxillary downward displacement following SARME. This theory is strongly supported by Xi et al.[29], as they observed a skeletal downward displacement of the maxilla with a clockwise rotation of the mandible and inferior chin displacement after only SARME[29]. Therefore, the results of Bianchi et al. and our study should be interpreted as a result of BiMEx instead of only MMD. Recently Öztürk et al. showed the

3D soft tissue effects of tooth-borne MMD and rapid maxillary expansion (RME) with a stereophotogrammetry system[30]. To our knowledge, and as the authors confirm, this is the first study evaluating the soft tissue effects of tooth-borne MMD using 3D imaging analysis techniques. Our results are broadly in line with Öztürk et al.[30], as they observed non-significant changes in bizygomatic width, bigonial width, biphiltrum width, upper vermillion height, and lower vermillion height. There was a significant increase in lower and total face height combined with nasal width increase. In contrast to our study, RME was achieved without surgery and a significant increase in mouth width was observed as well. Based on these findings, it seems that bone-borne and tooth-borne MMD, both as part of BiMEx, have comparable soft tissue effects. However, as yet there is still a lack of knowledge about the 3D soft tissue effects of MMD only. BiMEx seems to be beneficial for patients with a short lower third part of the face. On the other hand, BiMEx could lead to undesirable soft tissue effects for patients with a pre-existing gummy smile and long face. The transverse widening of the inter alar width after SARME could be undesirable as well for patients. Clinicians should communicate these possible soft tissue effects with the patients carefully during the planning of the orthognathic surgery.

In this thesis all SARME patients were expanded bilateral and so it can be assumed that this could affect the soft tissue effects in bilateral manner. However, unilateral crossbite also occurs in practice which could be an indication for unilateral SARME. With regard to this, Karabiber and Yilmaz observed that the soft tissue effects, although being significant, were not clinically important because of the small amount. Unilateral SARME did not lead to nasal asymmetry in their study[31]. Although unilateral SARME is beyond the scope of this thesis, it seems that there are no clinical relevant asymmetric effects in the nasal region.

Furthermore, it should be noted that our presented findings in **Part II**, *Chapter 4*, regarding skeletal effects in the nasal region broadly correlate with our study on 3D soft tissue effects of bone-borne MMD and tooth-borne SARME. We presented a significant mean increase of 2.20 mm in the inter-alar width (corresponding with piriform aperture lateral width) and a non-significant mean increase of 1.77 mm in the inter-alar curvature point width (corresponding with piriform aperture base width). It can be concluded that the skeletal effects do not project in the same proportion to the soft tissue effects regarding tooth-borne SARME. In addition, these findings are suggesting that besides the observed hard tissue effects other factors could influence these soft tissue effects like the circumvestibular approach, anterior nasal spine exposure and not applying an alar base cinch suture during surgery[32-34]. This is in line with Michaux et al. who studied the influence of a subspinal Le Fort I corticotomy on SARME. Their results showed that a subspinal Le Fort I corticotomy for SARME is safe procedure and prevents an increase in the columellar base post-operatively[34].

Long-term dento-skeletal effects of bone-borne MMD and tooth-borne SARME

Regarding the 3D dento-skeletal effects, it should be noted that the follow-up period is limited to 1 year. In **Part III**, *Chapter 6* and *7*, we presented the long-term dento-skeletal effects of bone-borne MMD and tooth-borne SARME using conventional methods like dental casts and posterior-anterior cephalograms. *Chapter 6* shows that the bone-borne MMD outcomes remain stable at 6.5 years and are in line with our study presented in **Part II**, *Chapter 4*. Based on this finding, we can conclude that bone-borne MMD is an effective and stable technique to widen the mandible in order to solve transverse mandibular discrepancies in the long-term. It should be noted that long-term dento-skeletal effects of tooth-borne MMD are not assessed in this thesis. Despite the fact that 3D dento-skeletal changes showed stable results for tooth-borne MMD at 1 year follow-up in **Part II**, *Chapter 4*, long-term outcomes are necessary to assess stability. King et al. has shown stable long-term results after treatment when using a custom-made combined tooth-borne and bone-borne (hybrid) distractor[14]. There was a significant decrease of the acquired expansion during the post-distraction orthodontic phase of treatment. Especially the premolar region showed more relapse than in our study. However, the long-term follow-up showed no significant skeletal or dental transverse changes at 6.0 years after retention and 7.5 years after distraction[14]. In another study from the same author's group, Durham et al. evaluated the long-term outcomes of tooth-borne (5.08 years) versus hybrid (6.07 years) MMD[35]. The only significant difference during the follow-up period was the central incisor contact point as measured from the study models. For this measurement, patients in the tooth-borne group showed a significant increase of 0.52 mm[35]. As shown in **Part II**, *Chapter 4*, this outcome may be related to the V-shape distraction gap and thus anterior mandibular skeletal tipping in the coronal plane for tooth-borne MMD. At the end of treatment, this distraction gap is closed with orthodontic alignment. Based on this finding, it can be assumed that the central incisors are partially dentally tipped medially in order to close the distraction gap since there is a significant anterior mandibular skeletal tipping. This could lead to relapse in the long-term, and thus significant increase of the inter central incisor width. However, it is notable that patients were provided removable retainers in this study[35]. For tooth-borne MMD, a bonded lingual retainer may be a simple and low-cost alternative for reducing the risk of this relapse in this region in the long-term.

In addition to bone-borne MMD, based on these long-term outcomes and our 3D dento-skeletal outcomes as shown in **Part II**, *Chapter 4*, it seems that MMD, either bone-borne, tooth-borne or hybrid, is an effective and stable technique to widen the mandible in order to solve transverse mandibular discrepancies in the long-term.

Regarding long-term dento-skeletal effects of SARME in **Part III**, *Chapter 7*, only a small decrease was observed in the canine and first molar region after distraction at 1 year post-operative. However, these distances remained significantly increased and the effects are the result of the orthodontic alignment which are comparable to those presented in **Part II**, *Chapter 4*. In addition, all dental distances remained significantly increased as well in the long-term at 6.5 years follow-up. In contrast to our 3D dento-skeletal outcomes as shown in **Part II**, *Chapter 4*, the internasal base distance did not significantly increase on the posteroanterior cephalograms suggesting a limitation of the applied conventional method. However, multiple studies have been performed using advanced 3D imaging analysis techniques regarding SARME[18-25]. These indicate that SARME is a well-established and stable technique. We therefore confirm with our long-term outcomes that tooth-borne SARME without transection of the pterygomaxillary junction is an effective and stable technique to widen the maxilla in order to solve transverse maxillary discrepancies.

Patient experience and satisfaction of MMD and SARME

From patient perspective, little is reported on patient experience and satisfaction of MMD and SARME in the literature. As a clinician, it is important to consider the expectations and perceptions of patients during the treatment.

Recently, Kustermans et al. studied the impact of tooth-borne MMD on TMJ in 68 patients. Morphological changes of the condyles were analysed by means of surface registration of 3D reconstructed CBCT scans pre-operatively and 1 year post-operatively. The results showed that the risk for TMJ symptoms was slightly increased from 18 to 25% at 14 months after tooth-borne MMD. However, the presence of TMJ symptoms before MMD was the only significant risk factor for having symptoms after MMD. No cases of extended condylar resorption were described and no correlation between morphological condylar changes (appositional and resorptive) and TMJ symptoms was observed. In this study, it must be strongly underlined that the observed substantial morphological changes occurred only in growing patients. There were no appositional and resorptive changes on more than 5% of the condylar surface for the older patients. Growth capacity seems not to be hindered for adolescent patients following MMD. Besides, only 5 patients underwent solitary MMD, while 63 patient underwent BiMEx[12]. Therefore, the results should be interpreted more as a result of BiMEx instead of only MMD since TMJ symptoms could occur also following only SARME.

In another recent study, Baranto et al. has reported the satisfaction outcomes using a self-made questionnaire on 30 patients who underwent SARME with a combined bone- and tooth-borne (hybrid) distractor. Twenty-nine of these patients were satisfied with this treatment and had no regrets. Other preoperative difficulties like biting, chewing, dental position, facial appearance, speech and self-esteem had improved with this treatment according to most of the patients. Worsening of pain in the TMJ region was uncommon among the patients (6.7%)[36]. These findings are comparable to our findings presented in **Part III**, *Chapter 8*. In this study, we asked the patients' opinions at different time points using two questionnaires:

- Post-surgical patient satisfaction questionnaire (PSPSQ), which consisted of nine questions regarding different aspects of orthognathic surgery as described by Posnick and Wallace[37]. The PSPSQ was based on the experiences of patients who underwent SARME with a mean follow-up of 6.5 years.
- Visual analogue scale questionnaire (VAS), which consisted of 8 questions regarding aesthetics, pain and distractor. The VAS was taken pre-operatively and at selected time points in the first year post-operatively.

PSPSQ showed high satisfaction rate after treatment period, and even though some patients had received secondary orthognathic surgery, high scores were obtained for an improved bite. VAS scores regarding satisfaction were in line with the PSPSQ and the aesthetic result was satisfactory for the patients. Moreover, pain scores were relatively low for both MMD and SARME. These pain scores for SARME measured directly post-operative were even lower than those reported by Hsu and Hsu who investigated immediate post-operative pain following orthognathic surgery (VAS 1.9 vs 3.06, respectively)[38]. These results can be used by clinicians to inform their patients about what they can expect in terms of pain and discomfort after MMD and SARME. In addition, this useful information may regulate patients' expectations.

It should be noted that the bone-borne distractor for MMD showed more disturbances than the tooth-borne distractor for SARME. For MMD, this could be related to the position of bone-borne distractors in the lower mucobuccal fold close to the mucosa of the lower lip, which could lead to pressure ulcers and discomfort. Due to the position of the bone-borne distractor and saliva with food accumulation, wound healing issues might occur.

Although bone-borne and tooth-borne MMD both are stable techniques to achieve transversal (dento-skeletal) expansion, the choice of distractor type is more depending 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[39] and do not need a second surgical procedure to be removed. 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.

Current practice of transverse mandibular and maxillary discrepancies among orthodontists and oral and maxillofacial surgeons in the Netherlands

In the orthodontic and oral and maxillofacial surgery literature, there are still a lot of controversies and a lack of consensus regarding indication for MMD and SARME, distractor type, latency period, distraction rate, overcorrection, and consolidation period for MMD and SARME. Therefore, as a clinician it is relevant to know what the current practice of transverse mandibular and maxillary discrepancies is. In **Part IV**, *Chapter 9*, this is obtained among orthodontists and oral and maxillofacial surgeons using a web-based survey in the Netherlands. This was provided by using the professional associations for Orthodontists (*'Nederlandse Vereniging van Orthodontisten'*, NVvO) and for Oral and Maxillofacial Surgeons (*'Nederlandse Vereniging voor Mondziekten, Kaak- en Aangezichtschirurgie'*, NVMKA). Three cases were presented which could be treated non-surgically and surgically. Participants were asked what treatment they preferred: no treatment, orthodontic treatment with optional extractions or surgically assisted orthodontic treatment. The web-based survey ended with questions on various technical aspects and any experienced complication. The results showed that in the Netherlands orthodontists generally prefer orthodontic treatment with optional extractions whereas oral and maxillofacial surgeons prefer surgically assisted orthodontic treatment for transverse mandibular and maxillary discrepancies. Regarding surgically assisted orthodontic treatment, MMD was less preferred, most likely due to lack of clinical experience or knowledge by both professions despite being a proven clinical surgical technique with stable long-term outcomes. Overall, there seems to be consensus on the technical aspects by both professions, except for the duration of the consolidation period. Complications that were encountered in daily practice in the Netherlands for MMD and SARME were mostly minor and manageable. Clinicians should be aware of a possible asymmetric or incorrect and undesired expansion following SARME and communicate this prior the treatment with their patients. Asymmetric or incorrect and undesired expansion following SARME could be a result of the minimal invasive trend of surgery with transection of only the piriform aperture, the zygomatic buttress and the midpalatinal suture without transection of the pterygomaxillary junction. This theory is also supported with the outcomes of Carvalho et al. in the systematic review of complications for SARME. When transection of the pterygomaxillary junction was not performed, there was an increased rate of asymmetric or incorrect and undesired expansion[40]. Due to the anatomical shape of the maxilla, the transection between the piriform aperture and the zygomatic buttress is almost never completely horizontal on both sides of the median osteotomy. Expanding the maxilla may therefore result in an asymmetric position in vertical direction. Other factors that could lead to an asymmetric expansion are broken or malfunctioning distractors.

Complications in MMD

Little has been reported regarding complications in MMD[41-43]. We assessed the complications systematically using the standardized Clavien-Dindo classification[44] and presented this in **Part IV**, *Chapter 10*. Our study showed that complications are mostly minor and bone-borne MMD is in general a safe technique to widen the mandible in order to solve transverse mandibular discrepancies. A significant part of the reported complications was distractor-related. Since bone-borne distractors are placed in the lower buccal fold, local inflammation or infection could occur due to saliva and food accumulation. In addition, this position is also not favorable for patient’s comfort. Only 6.8% of the included patients had mild TMJ related symptoms like clicking and tenderness. However, symptoms were transient, despite of a significant increase in inter condylar axes for bone-borne MMD as presented in **Part II**, *Chapter 4*. During MMD surgery, many complications can occur. Tooth damage is one of the major complications that should be prevented. In our study, we observed 1 patient (1.4%) requiring 2 teeth extractions after surgery following MMD due to periodontal decay. However, tooth damage could also occur during surgery due to a bad split when performing the vertical split osteotomy. Severe crowding could increase the risk of this, since there is less space for the osteotomy. In these cases of severe crowding, orthodontic alignment of the lower front incisors should be considered prior to surgery. This is in line with the study of Winsauer et al. since they demonstrated 2 techniques to separate the lower incisors prior to MMD to avoid tooth damage during surgery[45]. The authors showed that dento-alveolar expansion with a tooth-borne distractor by utilizing a one-step technique to separate the lower central incisors weakens the bone in the mandibular midline prior to surgery. This reduces the required forces for cutting the bone and therefore minimizes the risk of permanent tooth damage[45]. Another factor to minimize the risk of tooth damage is the osteotomy type. In this thesis, all MMD patients underwent a vertical split osteotomy whether or not combined with orthodontic alignment of the lower central incisors prior to surgery. A step wise vertical osteotomy between the lateral incisor and canine could minimize the risk of tooth damage as well since there is generally more space left compared to the lower central incisors. However, this technique is beyond the scope of this thesis and needs further research.

LIMITATIONS

This section discusses the limitations plus questions that could not be answered in this thesis and highlights future perspectives.

Since imaging techniques and software have become more sophisticated rapidly, it is possible to analyse dento-skeletal and soft tissue structures more accurately. In contrast to conventional radiographs, it is possible to perform 3D measurements of dento-skeletal and soft tissue structures on 3D reconstruction models using CBCT. This technique has less radiation exposure than the multislice computed tomography (MSCT) with highly realistic facial and skeletal information when compared with the 2D radiographs. FEM studies can analyse stress distribution during MMD in the mandible and the TMJ as presented in our systematic review in **Part I**, *Chapter 2*.

As has been discussed in this thesis, a limitation is the retrospective design of the studies regarding the 3D dento-skeletal and soft tissue effects of MMD and SARME in **Part II**, *Chapter 4* and *5*. Ideally, 3D dento-skeletal effects of bone-borne versus tooth-borne MMD are obtained with a prospective randomized clinical trial. In addition, larger sample sizes and long-term follow-up are recommended. In this thesis, in **Part II**, *Chapter 4* and *5*, the sample sizes and follow-up period were limited since the majority of the patients underwent additional orthognathic surgery within 1 year or due to incomplete 3D CBCT or stereophotogrammetry records following MMD and/or SARME.

Furthermore, 3D soft tissue effects of solitary MMD remain unanswered in this thesis, since all included MMD patients underwent simultaneous SARME in **Part II**, *Chapter 5*. Regarding the downward displacement of the soft tissue pogonion found in the present study, we think this is the effect of the maxillary downward displacement following SARME. This theory is strongly supported by Xi et al. as they observed a skeletal downward displacement of the maxilla with a clockwise rotation of the mandible and inferior chin displacement after only SARME[29]. Therefore, this should be interpreted as a result of BiMEx instead of MMD in **Part II**, *Chapter 5*.

On the other hand, in **Part III**, *Chapter 6* and *7*, long-term dento-skeletal outcomes were obtained with a prospective study design. However, it should be noted that only conventional imaging techniques were used in these studies. Another limitation is that there were no tooth-borne MMD patients included, which makes the comparison of dento-skeletal stability with bone-borne MMD in the long-term impossible. In addition to **Part III**, *Chapter 8*, it would be interesting to compare the PSPSQ among bone-borne and tooth-borne MMD. Only then conclusions could be drawn regarding the differences in experiences by patients which could support clinicians with their choice of type distractor.

FUTURE PERSPECTIVES

Regarding MMD, we performed a vertical split osteotomy in all patients in this thesis.

However, other surgical approaches such as a step wise vertical osteotomy between the lateral incisor and canine may result in different biomechanical masticatory loads and distraction forces. In particular, when comparing dento-skeletal effects of bone-borne versus tooth-borne MMD. Given the probability of less tooth damage in severe crowding cases, the effects of this osteotomy type warrant further investigation.

Nowadays minimal invasive trend of surgery is becoming more popular, which leads to less post-operative morbidity and health care costs. A new technique is introduced to solve maxillary transverse discrepancies named Miniscrew-Assisted Rapid Maxillary Expansion (MARME)[46-48]. This technique is performed under local anesthesia and without osteotomies, in which two or four miniscrews are incorporated into a RME distractor and is fixated to the palatal bone (hybrid). In **Part I**, *Chapter 3*, we presented the current knowledge on MARME as a non-surgical maxillary expansion modality in skeletally mature non-syndromic patients in a systematic review of the current literature. MARME is currently applied in our department, and data is being gathered for future clinical studies. We aim to research these data with accurate (automated) 3D imaging analysis techniques, as developed and published for bony and soft tissue structures on 3D reconstruction models[27,28,49]. Furthermore, at our department new software pipelines are being developed to measure soft tissue effects of orthognathic surgery more accurately. With these software tools the accuracy of pre-operative planning can be increased. Moreover, application of virtual reality (VR) could be possible. VR can be helpful for patients in understanding the surgical procedures like MMD and SARME. Therefore, VR could increase patient’s experience and satisfaction levels. In addition, augmented reality (AR) is a potential alternative for navigation during surgery[50]. Research on this topic is already being performed at our department[51]. However, further developments on AR could assist the surgeon during a MMD and/or SARME when performing the osteotomy lines based on the pre-operative planning. This could be applied for challenging cases due to severe crowding or craniofacial deformities.

Last, functional loads of the TMJ remain unclear following MMD independently of distractor type. TMJ related symptoms were transient and not permanent in this thesis, however condylar appositional and resorptive changes after bone-borne versus tooth-borne MMD for adults need still to be clarified using CBCT. Ideally, this should be studied in a randomized controlled trial. Only then risk for potential occlusal changes such as open bite or retrognathia could be clarified.

CONCLUSIONS

3D CBCT analysis for dento-skeletal effects of bone-borne versus tooth-borne MMD and tooth-borne SARME showed stable dento-skeletal effects after 1 year, showing them to be reliable treatment options for transverse mandibular and maxillary discrepancies. Bone-borne MMD showed a more parallel wise distraction gap at basal bone level, whereas tooth-borne MMD showed a V-shape distraction gap indicating anterior mandibular skeletal tipping in the coronal plane and suggesting dento-skeletal tipping of the mandibular canine and first premolar. There were no significant changes seen in ramal angle and inter condylar distance for MMD, despite significant inter condylar axes increase for bone-borne MMD. For tooth-borne SARME, only piriform aperture base width remained significantly increased when combined with bone-borne MMD (**Fig. 1**).

In the long-term at 6.5 years, the bone-borne MMD outcomes remain stable. Furthermore, at 6.5 years follow-up our (long-term) outcomes confirm that tooth-borne SARME without transection of the pterygomaxillary junction is an effective and stable technique to widen the maxilla.

Regarding the overlying soft tissue in the orofacial area, bone-borne MMD combined with tooth-borne SARME leads to a downward displacement of the soft tissue pogonion with a tendency towards an increase in the inter-soft tissue gonion distance. In addition, it leads to a transverse widening of the inter alar width and a tendency for an increase of the inter alar curvature point width. However, in general, patients who underwent MMD and SARME are very satisfied with their treatment.

Regarding the current practice for transverse mandibular and maxillary discrepancies in the Netherlands, generally orthodontists prefer orthodontic treatment with optional extractions and oral and maxillofacial surgeons prefer surgically assisted orthodontic treatment for transverse mandibular and maxillary discrepancies. MMD seems less preferred. Regarding complications, encountered in daily practice in the Netherlands, for MMD and SARME these are mostly minor and manageable. Clinicians should be aware of a possible asymmetric or incorrect and undesired expansion following SARME.

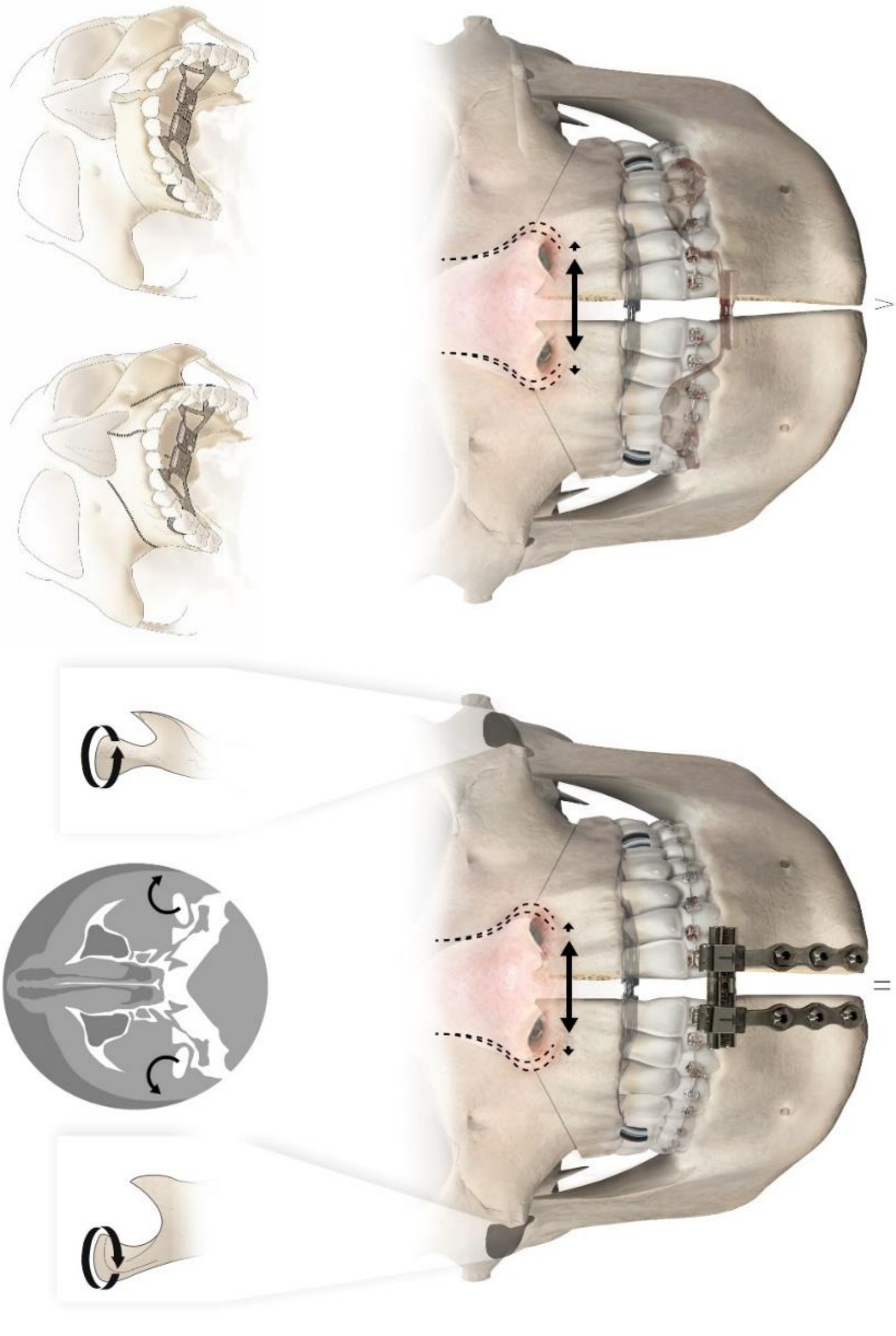

Fig. 1. 3D dento-skeletal and soft tissue effects of bone-borne vs tooth-borne MMD and tooth-borne SARME.

Complications in MMD encountered in this thesis were mostly mild, transient and manageable. There was no need observed for any re-operation. Only 6.8% of the included patients had mild TMJ related symptoms like clicking and tenderness. However, symptoms were transient, despite of a significant increase in inter condylar axes for bone-borne MMD.

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VI

(DUTCH) SUMMARY

11

Summary

SUMMARY

This thesis is a study of various three-dimensional (3D) and clinical aspects of Mandibular Midline Distraction (MMD) and Surgically Assisted Rapid Maxillary Expansion (SARME). Both surgical techniques are to widen respectively the mandible and maxilla using the principles of distraction osteogenesis to correct transverse discrepancies.

The objectives of this thesis were as follows:
- 3D dento-skeletal effects of bone-borne versus tooth-borne MMD and tooth-borne SARME.
- 3D soft tissue effects of MMD and SARME.
- Long-term dento-skeletal effects of bone-borne MMD and tooth-borne SARME.
- Patient experience and satisfaction of MMD and SARME.
- Current practice of transverse mandibular and maxillary discrepancies among orthodontists and oral and maxillofacial surgeons in the Netherlands.
- Complications in MMD.

Based on these objectives, this thesis is divided into four parts:

Part I General introduction and literature

Part II Retrospective clinical studies

Part III Prospective clinical studies

Part IV Survey and complications

Part V General discussion and conclusions, limitations and future perspectives

Part I is the general introduction and provides an overview of the literature. *Chapter 1* consists of the general introduction. A systematic overview of the literature on the 3D aspects of MMD using different distractor types was provided and evaluated in *Chapter 2*. A limited amount of studies was available with low level of evidence and small sample sizes. Bone-borne distractor seems preferable when taking skeletal effects into account. Tooth-borne distraction leads to significant dental tipping. Hybrid distractor combined with parasymphyseal step osteotomy seemed to be most stable under functional masticatory loads. No permanent TMJ symptoms were reported and little is known about soft tissue effects. Based on these findings more studies should be conducted to clarify these aspects.

In *Chapter 3* a second systematic overview was presented. The focus of this systematic review lied on Miniscrew-Assisted Rapid Maxillary Expansion (MARME). Following the trend of minimal invasive surgery, this is a new technique to solve maxillary transverse discrepancies performed under local anesthesia without osteotomies. The aim of this systematic overview was to evaluate the current evidence on MARME performed in skeletally mature patients. MARME seems effective for achieving adequate dental, skeletal and upper airway expansion in patients aged around 20 years. However, long-term outcomes and effects in older patients are limited. MARME induced paranasal soft tissue changes. Care should be taken in periodontally compromised patients and periodontal conditions should be monitored.

Part II consists of the retrospective clinical studies with the focus on 3D dento-skeletal effects and soft tissue effects of MMD and SARME. In *Chapter 4* a retrospective observational study was conducted to provide a 3D evaluation of the dento-skeletal effects following bone-borne vs tooth-borne MMD and tooth-borne SARME. All included 30 patients had undergone MMD (20 bone-borne MMD; 10 tooth-borne MMD). Twenty bone-borne MMD and 8 tooth-borne MMD patients had simultaneously undergone tooth-borne SARME. Cone beam computed tomography (CBCT) records were taken pre-operative (T1), immediately post-distraction (T2) and 1 year post-operative (T3). At T1 vs T3, canine ($p=0.007$) and first premolar ($p=0.005$) showed significant expansion on tip level for tooth-borne MMD. This was however not significant on apex level, indicating tipping. At T1 vs T3, the mean expansion on canine, first premolar and first molar tip level remained significant ($p<0.05$) for bone-borne and tooth-borne MMD, and for tooth-borne SARME. Bone-borne MMD showed a more parallel distraction gap, whereas tooth-borne MMD showed V-shape. No significant ($p>0.05$) changes were seen in the ramal angle and inter condylar distance for MMD, despite significant ($p=0.017$) inter condylar axes increase for bone-borne MMD. Tooth-borne SARME combined with bone-borne MMD showed a (reverse) V-shape maxillary widening. 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-operative.

Regarding the correlation of these dento-skeletal effects with the overlying soft tissue in the orofacial region, in *Chapter 5* a retrospective observational study was conducted to provide a 3D evaluation of the soft tissue effects following MMD and/or SARME. From 2008 to 2013, patients who underwent MMD and/or SARME were included in this study. Stereophotogrammetry records were taken at fixed time points: pre-operative (T1), direct post-distraction (T2) and 1-year post-operative (T3). Analyses were performed with an automatic 3D facial landmarking algorithm. Twenty patients were included that all had undergone SARME. Twelve patients had undergone bimaxillary expansion (BiMEx), a combination of MMD and SARME. The results showed a significant downward displacement of the soft tissue pogonion. Furthermore, there was a significant mean increase of 2.20 mm for the inter alar width and a non-significant mean increase of 1.77 mm for the inter alar curvature point width. In conclusion, automatic stereophotogrammetry landmarking analysis of the soft tissue effects showed a downward displacement of the soft tissue pogonion following BiMEx and a transversal widening of the inter alar width and a tendency for an increase of the inter alar curvature point width after SARME.

Part III consists of the prospective clinical studies with the focus on the long-term effects of both MMD and SARME. In *Chapter 6* a prospective observational study was conducted with a retrospective cohort on the long-term stability and biomechanical effects of MMD. Included were 17 MMD patients, of whom 9 completed the long-term follow-up with a mean of 6.5 years. In all patients, a bone-borne distractor was used. Dental casts and postero-anterior (PA) cephalograms were taken at fixed time points: pre-operative (T1), direct post-distraction (T2), 1-year post-operative (T3) and long-term follow-up (T4). The greatest overall transverse expansion (T1-T4) occurred in the inter first premolar distance (4.1 ± 0.76 mm, $p<0.05$). The inter condylar distance did not change significant ($p>0.05$) during all phases of the study. An increase of ramal angle was observed initially. However, no difference was noted in the long-term. This study showed that MMD is a stable method to expand the mandible, in the long-term as well.

In *Chapter 7* the results of our long-term follow-up of 6.5 years for SARME were presented. Seventeen patients who had been treated with SARME and prospectively followed were invited for long-term follow-up using dental casts and PA cephalograms. Bone-borne and tooth-borne distractors were used in 8 and 9 patients, respectively. In the study of dental casts, there was a significant increase in transverse width in the canine ($p<0.001$), first premolar ($p<0.001$) and first molar ($p=0,001$) and these remained stable in the long-term. The arch length did not increase significantly, but the palatal width increased significantly in the premolar ($p<0.001$) and molar ($p=0.001$) regions. On the PA cephalograms the width of the inferior part of the maxilla was increased, but not significantly so. There were no significant changes at the nasal base. We conclude that SARME is a predictable technique to widen the maxilla in the long-term.

Chapter 8 aimed to assess patient experience and satisfaction with MMD and SARME in two different groups. The first group answered the post-surgical patient satisfaction questionnaire on a 7-point Likert scale during a long-term follow-up recall. The second group answered a visual analogue scale questionnaire (range: 0-10) with different questions regarding experience and satisfaction, at different time points during the first year of treatment. In both groups, 17 patients were included. Regarding the post-surgical patient satisfaction questionnaire, a mean satisfaction rate of 6.4 was reported, with a mean follow-up of 6.5 years post-operatively. In the visual analogue scale group, the mean satisfaction rate was 8.0 and did not significantly differ from the expectations pre-operative (p=0.96). Both procedures showed relatively low pain scores, although a significant higher score was observed in MMD post-operatively (p=0.00051). Regarding hindrance, the scores were moderate; the bone-borne distractor in the mandible gained higher scores than the tooth-borne distractor in the mandible. In conclusion, both MMD and SARME gain high satisfaction rates.

Part IV focuses on the current practice for transverse mandibular and maxillary discrepancies in the Netherlands and on the complications in MMD.

In *Chapter 9* an overview was provided of the current practice for transverse mandibular and maxillary discrepancies in the Netherlands using a web-based survey. Orthodontists (ORTHO) and Oral and Maxillofacial Surgeons (OMFS) in the Netherlands were invited to the web-based survey via their professional association. Three cases were presented which could be treated non-surgically and surgically. Participants were asked what treatment they preferred: no treatment, orthodontic treatment with optional extractions or surgically assisted orthodontic treatment.

The web-based survey ended with questions on various technical aspects and any experienced complication. Invitation was sent to all 303 members of professional association for ORTHO and to all 379 members of professional association for OMFS. Overall response number was 276 (response rate of 40.5%), including 127 incomplete responses. Generally, ORTHO prefer orthodontic treatment with optional extractions and OMFS lean towards surgically assisted orthodontic treatment. MMD appears to be less preferred, possibly due to lack of clinical experience or knowledge by both professions despite being proven clinical stable surgical technique with stable long-term outcomes. There seems to be consensus on technical aspects by both professions, however, there are various thoughts on duration of consolidation period. Complications are mostly minor and manageable.

Regarding complications, in *Chapter 10* the amount and burden of complications in MMD were assessed. A retrospective cohort study was performed on patients who underwent MMD between 2002 and 2014. Patient records were obtained and individually assessed for any complications. Complications were graded using the Clavien-Dindo classification system (CDS). Seventy-three patients were included of which 33 were males and 40 were females. The mean follow-up was 2.1 years. Twenty-nine patients had minor complications, grades I and II. Two patients had a grade IIIa and three patients had a grade IIIb complication. Common complications were pressure ulcers, dehiscence, and (transient) sensory disturbances of the mental nerve. This study showed that although MMD is a relatively safe method, complications can occur. Mostly the complications are mild, transient, and manageable without the need for any reoperation.

Part V is the general discussion and reviewed our findings in a broader perspective. It provides an overview of the conclusions and several methodological limitations. Lastly, future perspectives are presented.

12

Dutch summary
(Nederlandse samenvatting)

DUTCH SUMMARY (NEDERLANDSE SAMENVATTING)

Dit proefschrift is een studie over verschillende driedimensionale (3D) en klinische aspecten van Mandibular Midline Distraction (MMD) en Surgically Assisted Rapid Maxillary Expansion (SARME). Deze chirurgische technieken hebben als doel om respectievelijk de onder- en bovenkaak te verbreden ter correctie van transversale discrepanties. Hierbij wordt er gebruik gemaakt van de distractie osteogenese principes.

De doelstellingen van dit proefschrift waren als volgt:

- 3D dento-skeletale effecten van bot-gedragen versus tand-gedragen MMD en tand-gedragen SARME.
- 3D weke delen effecten van MMD en SARME.
- Langetermijn dento-skeletale effecten van bot-gedragen MMD en tand-gedragen SARME.
- Patiënten ervaringen en tevredenheid over MMD en SARME.
- Huidige toegepaste standaard in transversale mandibulaire en maxillaire discrepanties door orthodontisten en mond-, kaak- en aangezichtschirurgen (MKA-chirurgen) in Nederland.
- Complicaties bij MMD.

Op basis van deze doelstellingen is dit proefschrift opgedeeld in vier delen:

Deel I **Algemene introductie en literatuur**

Deel II **Retrospectieve klinische onderzoeken**

Deel III **Prospectieve klinische onderzoeken**

Deel IV **Vragenlijst en complicaties**

Deel V **Algemene discussie en conclusies, beperkingen en toekomstige onderzoeken**

Deel I omvat een algemene introductie en geeft een overzicht van de literatuur. *Hoofdstuk 1* is de algemene introductie. Een systematisch overzicht van de literatuur over de 3D aspecten van MMD werd gegeven en geëvalueerd in *Hoofdstuk 2*. De nadruk lag hierin op de verschillende typen distractoren. Er was op dit gebied slechts een beperkt aantal studies beschikbaar welke uit kleine patiënten populaties bestonden en van lage kwaliteit waren. Een bot-gedagen distractor had de voorkeur wanneer rekening werd gehouden met skeletale effecten. Een tand-gedragen distractor was gerelateerd aan significante dentale tipping. Een hybride distractor in combinatie met parasymfysaire stap osteotomie was het meest stabiel onder functionele kauw belastingen. Er werden geen permanente TMJ symptomen gemeld en er is weinig bekend over de weke delen effecten. Er is derhalve vraag naar meer studies om deze aspecten te verduidelijken.

In *Hoofdstuk 3* werd een tweede systematisch literatuuroverzicht gepresenteerd. De focus van dit overzicht lag op Miniscrew-Assisted Rapid Maxillary Expansion (MARME). Dit is een nieuwe techniek om maxillaire transversale discrepanties te behandelen. MARME wordt uitgevoerd onder lokaal anesthesie zonder een osteotomie en valt derhalve onder minimale invasieve chirurgie. Het doel van dit systematisch literatuuroverzicht was om de effectiviteit van MARME te evalueren bij volwassen patiënten. We ontdekten dat MARME effectief is voor het bereiken van een adequate tand-, skelet- en bovenste luchtwegexpansie bij patiënten van ongeveer 20 jaar. De lange termijn resultaten en effecten bij oudere patiënten zijn echter beperkt. MARME veroorzaakte veranderingen in de paranasale weke delen. Voorzichtigheid is geadviseerd bij patiënten met parodontale aandoeningen.

Deel II bestaat uit de retrospectieve klinische studies met de focus op 3D dento-skeletale effecten en weke delen effecten van MMD en SARME. In *Hoofdstuk 4* werd een retrospectieve observationele studie uitgevoerd om een 3D evaluatie te geven van de dento-skeletale effecten na bot-gedragen versus tand-gedragen MMD en tand-gedragen SARME. Alle geïncludeerde 30 patiënten hadden MMD ondergaan (20 bot-gedragen MMD; 10 tand-gedragen MMD). Twintig bot-gedragen MMD patiënten en 8 tand-gedragen MMD patiënten hadden gelijktijdig een tand-gedragen SARME ondergaan. Cone beam computertomografie (CBCT) opnamen werden pre-operatief (T1), direct na distractie (T2) en 1 jaar post-operatief (T3) uitgevoerd. Op T1 versus T3 was er op cuspidaat ($p=0.007$) en eerste premolaar ($p=0.005$) tip niveau een significante expansie te zien bij de tand-gedragen MMD. Dit was echter niet significant op apex niveau, wat wijst op tipping. Op T1 versus T3 bleef de gemiddelde expansie op tip niveau van de cuspidaat, eerste premolaar en eerste molaar significant ($p<0.05$) voor bot- en tand-gedragen MMD, en voor tand-gedragen SARME. Bot-gedragen MMD toonde een meer parallelle distractie opening, terwijl tand-gedragen MMD een V-vorm toonde. Er werden geen significante ($p>0.05$) veranderingen gezien in de ramus hoek en inter condylaire afstand voor MMD, ondanks een significante ($p=0.017$) toename van de inter condylaire as hoek voor bot-gedragen MMD. Tand-gedragen SARME gecombineerd met bot-gedragen MMD toonde een (omgekeerde) V-vormige maxillaire verbreding. Concluderend, de 3D CBCT analyse voor dento-skeletale effecten van bot-gedragen versus tand-gedragen MMD en tand-gedragen SARME toonde stabiele dento-skeletale effecten 1 jaar post-operatief.

Met betrekking tot de correlatie van deze dento-skeletale effecten met de overliggende weke delen in het orofaciale gebied, werd in *Hoofdstuk 5* een retrospectieve observationele studie uitgevoerd om een 3D evaluatie te geven van de weke delen effecten na MMD en/of SARME. Van 2008 tot 2013 werden in deze studie patiënten geïncludeerd die MMD en/of SARME ondergingen. Stereofotogrammetrie opnamen werden pre-operatief (T1), direct na distractie (T2) en 1 jaar post-operatief (T3) gemaakt. Analyses werden uitgevoerd met een automatisch 3D algoritme voor gezichtsherkenning. Er werden 20 patiënten geïncludeerd die allemaal SARME hadden ondergaan. Hiervan hadden 12 patiënten een bimaxillaire expansie (BiMEx) ondergaan, wat een combinatie van MMD en SARME is. De resultaten toonden een significante neerwaartse verplaatsing van de weke delen pogonion (kinpunt). Verder was er een significante gemiddelde toename van 2.20 mm voor de inter alaire (neusvleugel) breedte en een niet-significante gemiddelde toename van 1.77 mm voor de inter alaire (neusvleugel basis) breedte. Concluderend, de automatische stereofotogrammetrie landmark analyse van de weke delen effecten toonde een neerwaartse verplaatsing van de weke delen pogonion/kinpunt na BiMEx en een transversale verbreding van de inter alaire (neusvleugel) breedte. Daarnaast was er een tendens tot een toename van de inter alaire (neusvleugel basis) na SARME.

Deel III bestaat uit de prospectieve klinische onderzoeken met de focus op de lange termijn effecten van zowel MMD als SARME. In *Hoofdstuk 6* werd een prospectieve observationele studie uitgevoerd met een retrospectief cohort naar de lange termijn stabiliteit en biomechanische effecten van MMD. Hierin waren 17 MMD patiënten geïncludeerd, van wie 9 de lange termijn follow-up hadden voltooid (gemiddeld 6.5 jaar). Bij alle patiënten werd een bot-gedragen distractor gebruikt. Afdrukmodellen en posterior-anterieure (PA) cephalogrammen werden pre-operatief (T1), direct na distractie (T2), 1 jaar post-operatief (T3) en op de lange termijn follow-up (T4) genomen. De grootste transversale expansie op T1-T4 vond plaats in eerste premolaar regio (4.1 ± 0.76 mm, $p<0.05$). De inter condylaire afstand veranderde niet significant ($p>0.05$) in alle fasen van de studie. Aanvankelijk werd een toename van de ramus hoek waargenomen, op lange termijn werd echter geen verschil meer geconstateerd. Deze studie toonde aan dat MMD een betrouwbare methode is om de onderkaak te verbreden, en tevens stabiel is op de lange termijn.

In *Hoofdstuk 7* werden de resultaten van onze lange termijn follow-up van 6.5 jaar voor SARME gepresenteerd. Zeventien patiënten die een SARME hadden ondergaan en prospectief werden gevolgd, werden uitgenodigd voor de lange termijn follow-up voor het vervaardigen van afdrukmodellen en PA cephalogrammen. Bij respectievelijk 8 en 9 patiënten werden bot- en tand-gedragen distractoren gebruikt. Er was een significante transversale expansie in cuspidaat ($p<0.001$), eerste premolaar ($p<0.001$) en eerste molaar (p=0.001) regio. Deze expansies bleven op lange termijn stabiel. De booglengte nam niet significant toe, maar de palatinale breedte nam wel significant toe in de premolaar (p<0.001) en molaar (p=0.001) regio. Er waren geen significante veranderingen in de neusbasis op de PA cephalogrammen. Concluderend is SARME een betrouwbare techniek om de bovenkaak te verbreden, waarvan de resultaten op de lange termijn stabiel blijven.

Hoofdstuk 8 beoordeelt de ervaring en tevredenheid van patiënten met MMD en SARME in twee verschillende patiënten groepen. De eerste groep beantwoordde de post-operatieve tevredenheidsvragenlijst op een 7-punts Likert-schaal op de lange termijn. De tweede groep beantwoordde een visueel analoge schaal (VAS) vragenlijst (schaal: 0-10) met verschillende vragen over ervaring en tevredenheid op verschillende tijdstippen tijdens het eerste jaar van de behandeling. In beide groepen werden 17 patiënten geïncludeerd. Met betrekking tot de postoperatieve patiënt tevredenheidsvragenlijst werd een gemiddelde tevredenheid van 6.4 gerapporteerd, met een gemiddelde follow-up van 6.5 jaar post-operatief. In de VAS vragenlijst groep was er een gemiddelde tevredenheid van 8.0, welke niet significant verschilde van de pre-operatieve verwachtingen (p=0.96). Beide procedures lieten relatief lage pijnscores zien, hoewel postoperatief een significant hogere score werd waargenomen bij MMD (p=0.00051). Wat betreft ongemak waren de scores matig; de bot-gedragen distractor in de onderkaak behaalde hogere scores dan de tand-gedragen distractor in de onderkaak. Concluderend behaalden in het algemeen zowel MMD als SARME hoge tevredenheidscijfers.

Deel IV richt zich op de toegepaste standaard in transversale mandibulaire en maxillaire discrepanties door orthodontisten en mond-, kaak- en aangezichtschirurgen (MKA-chirurgen) in Nederland. Tevens werden de complicaties bij MMD belicht.

In *Hoofdstuk 9* werd een overzicht gegeven van de toegepaste standaard in transversale mandibulaire en maxillaire discrepanties in Nederland met behulp van een online vragenlijst. Orthodontisten (ORTHO) en MKA-chirurgen (OMFS) in Nederland werden via hun beroepsvereniging uitgenodigd voor de online vragenlijst. Er werden drie casussen gepresenteerd die zowel niet-chirurgisch als chirurgisch konden worden behandeld. Aan de deelnemers werd gevraagd welke behandeling hun voorkeur had: geen behandeling, orthodontische behandeling met optionele extracties of chirurgisch geassisteerde orthodontische behandeling.

De online vragenlijst eindigde met vragen over verschillende technische aspecten en eventuele ervaren complicaties. De uitnodiging is verstuurd naar alle 303 leden van de ‘*Nederlandse Vereniging van Orthodontisten*’ en naar alle 379 leden van de ‘*Nederlandse*

Vereniging voor Mondziekten, Kaak- en Aangezichtschirurgie'. Het totale responsaantal was 276 (responspercentage van 40.5%), inclusief 127 onvolledige antwoorden. Over het algemeen geeft ORTHO de voorkeur aan orthodontische behandeling met optionele extracties, terwijl OMFS meer naar de chirurgisch geassisteerde orthodontische behandeling neigt. MMD lijkt minder de voorkeur te hebben. Mogelijk is dit vanwege een gebrek aan klinische ervaring of kennis bij beide beroepsgroepen, ondanks het feit dat het een bewezen klinisch stabiele chirurgische techniek betreft met stabiele lange termijn resultaten. Er lijkt consensus te bestaan over de technische aspecten bij beide beroepsgroepen, echter zijn er verschillende meningen over de duur van de consolidatieperiode. Complicaties zijn meestal klein en te behandelen.

Wat betreft complicaties bij MMD, werd in *Hoofdstuk 10* een retrospectieve cohortstudie uitgevoerd bij patiënten die tussen 2002 en 2014 MMD ondergingen. Patiëntendossiers werden geraadpleegd en beoordeeld op eventuele complicaties. Complicaties werden gescoord met behulp van het Clavien-Dindo classificatiesysteem (CDS). Drieënzeventig patiënten werden geïncludeerd, waarvan 33 mannen en 40 vrouwen. De gemiddelde follow-up was 2.1 jaar. Negenentwintig patiënten hadden kleine complicaties, graad I en II. Twee patiënten hadden een complicatie van graad IIIa en drie patiënten hadden een complicatie van graad IIIb. Veelvoorkomende complicaties waren decubitus, dehiscentie en (voorbijgaande) sensorische stoornissen van de nervus mentalis. Uit dit onderzoek bleek dat, hoewel MMD een relatief veilige methode is, er complicaties kunnen optreden. De meeste complicaties zijn mild, van voorbijgaande aard en behandelbaar zonder dat een nieuwe operatie nodig is.

Deel V omvat de algemene discussie waarin onze bevindingen in een breder perspectief worden besproken. Het geeft een overzicht van de conclusies en een aantal methodologische beperkingen. Tot slot worden er klinische aanbevelingen gedaan en suggesties voor toekomstig onderzoek.

VII

EPILOGUE

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Curriculum Vitae

CURRICULUM VITAE

Personal data

Name:	Gül
First name:	Atilla
Address:	Saftlevenstraat 26D
Postal code:	3015 BP
Place of residence:	ROTTERDAM
Telephone:	+31 6 16 17 19 32
Email:	a.gul@erasmusmc.nl
Date of birth:	22-06-1988
Place of birth:	AMSTERDAM
Sex:	Man
Nationality:	Dutch

Educational

Kind of education:	**WO - Dentistry (TOVA), BSc, MSc**
Establishment:	Radboud University Nijmegen - Radboudumc
Place:	Nijmegen
Year:	2015-2018
Diploma:	Yes

Kind of education:	**WO - Medicine, MSc**
Establishment:	Erasmus University Rotterdam - Erasmus MC
Place:	Rotterdam
Year:	2012-2015
Diploma:	Yes

Kind of education:	**WO - Medicine, BSc**
Establishment:	Erasmus University Rotterdam - Erasmus MC
Place:	Rotterdam
Year:	2008-2012
Diploma:	Yes

Kind of education: **WO - Architecture, BSc**
Establishment: Technical University of Delft - TU Delft
Place: Delft
Year: 2007-2008
Diploma: No

Kind of education: **WO - Pharmacy, BSc**
Establishment: University of Utrecht - UMC Utrecht
Place: Utrecht
Year: 2006-2007
Diploma: No

Kind of education: **VWO**
Establishment: Bredero College
Place: Amsterdam
Year: 2000-2006
Diploma: Yes

General working experience

2022 Feb.-present	Fellow Head and Neck Surgery at Department of Oral and Maxillofacial Surgery, Erasmus MC
2022 Feb.-present	Oral and Maxillofacial Surgeon and Staff Member at Department of Oral and Maxillofacial Surgery, Erasmus MC
2021 Aug.-present	Commissielid Werkgroep Esthetische Aangezichtschirurgie (WEAC-NVMKA)
2021 Jul.-Dec.	Resident (AIOS) at Department of Oral and Maxillofacial Surgery, Elisabeth-TweeSteden Hospital, Tilburg
2019-2021 Dec.	Adviserend AIOS-lid - Registratiecommissie Tandheelkundige Specialismen (RTS): 26-02-2020: RTS opleiding visitatie, Rijnstate ziekenhuis Arnhem 16-06-2020: RTS opleiding visitatie, Radboudumc Nijmegen 17-06-2020: RTS opleiding visitatie, MKA Kennemer & Meer Haarlem 24-03-2021: RTS opleiding visitatie, Amphia Ziekenhuis Breda 01-04-2021: RTS opleiding visitatie, Medisch Centrum Leeuwarden 13-04-2021: RTS opleiding visitatie, UMC Utrecht - *Online* 01-10-2021: RTS opleiding visitatie, Elkerliek Ziekenhuis Helmond
2018-2021 Jun.	Resident (AIOS) & PhD candidate at Department of Oral and Maxillofacial Surgery, Erasmus MC

2017 Aug.-Dec.	Resident (ANIOS) & PhD candidate at Department of Oral and Maxillofacial Surgery, Erasmus MC
2009-2010	Turkish medical interpreter, Children's Hospital Erasmus MC - Sophia
2009-2010	Student-assistant at Department of Ophthalmology, Erasmus MC

Language skills

Dutch:	Native
Turkish:	Native
English:	Professional

Interests

Interior and exterior home designing and renovating, real estate, cars, travelling and skiing.

Memberships

Nederlandse Vereniging voor Mondziekten, Kaak- en Aangezichtschirurgie (NVMKA)
European Association for Cranio-Maxillo-Facial Surgery (EACMFS)
Arbeitsgemeinschaft für Osteosynthesefragen (AO) - Cranio-Maxillo-Facial Surgery (CMF)
Registratiecommissie Tandheelkundige Specialismen (RTS)
Werkgroep Esthetische Aangezichtschirurgie (WEAC-NVMKA)
Nederlandse Vereniging voor Orale Implantologie (NVOI)

References

All Staff Members of the Department of Oral and Maxillofacial Surgery, Erasmus MC, Rotterdam
I. ten Hove, Head and Neck Surgeon, Leiden UMC
All Staff Members of the Department of Oral and Maxillofacial Surgery, Elisabeth-TweeSteden Hospital, Tilburg

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UNDER REVIEW

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J Craniomaxillofac Surg.

SCAN ME

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PhD Portfolio

PHD PORTFOLIO

Summary of PhD training and teaching

Name PhD student: Atilla Gül	PhD period: 2013-2022
Erasmus MC Department: Oral and Maxillofacial Surgery	Promotor(s): prof.dr. E.B. Wolvius
Research School: Medicine	Supervisor: dr. M.J. Koudstaal

1. PhD training

	Year	**Workload (Hours/ECTS)**
General courses		
- Research Integrity	2014	0.3
- Consultation center for Patient Oriented Research (CPO) Course	2014	0.3
- OpenClinica Course	2015	0.5
- GemTracker Course	2017	0.5
- LimeSurvey Course	2017	0.5
- Teach the Teacher II Course	2019	0.3
Specific courses (e.g. Research school, Medical Training)		
- Medical training	2008-2015	
- Dentistry training	2015-2018	
- Residency Oral and Maxillofacial Surgery	2017-2021	
Seminars and workshops		
- Kaakchirurg In Opleiding cursus		
Dento-Alveolaire chirurgie	2018	0.5
Implantologie	2019	1.0
Oral medicine	2019	1.0
Trauma	2020	1.0
Orthognatische chirurgie	2020	1.5
Oncologie	2021	1.0
TMJ	2021	1.0
- AO Foundation - Soft-Tissue Management, Hamburg, Germany	2018	1.5
- AO CMF - Management of Facial Trauma, Uniondale, New York, USA	2018	1.5
- Mini Around the Nose hands-on training course, Radboudumc Nijmegen	2021	0.5
- PAO-T cursus: Stralingshygiëne voor gebruik van CBCT voor tandartsen, orthodontisten en kaakchirurgen, Radboudumc Nijmegen	2021	1.5
- Observership Cosmetic Facial Surgery (6 weeks) - UMC Groningen *(supervisors: dr. Jansma & dr. Schepers)*	2021	6.0
- NVvO Basiscursus Oncologie 28 maart t/m 1 april - Ellecom	2022	2.5

Presentations		
- IAOMS-AÇBID Joint Congress, Antalya, Turkey - Three-Dimensional Soft Tissue Effects of Mandibular Midline Distraction and Surgically Assisted Rapid Maxillary Expansion: An Automatic Stereophotogrammetry Landmarking Analysis *EACMFS Award Best Oral Presentation: first prize*	2018	1.0
- NVMKA Voorjaarsvergadering, Maastricht - Driedimensionele weke delen effecten van Mandibular Midline Distraction en Surgically Assisted Rapid Maxillary Expansion: Een automatische stereofotogrammetrie landmark analyse	2018	1.0
- 101st AAOMS Annual Meeting, Scientific Sessions and Exhibition Boston, Massachusetts, USA, Sept. 16-21, 2019 - Patient Experience, Satisfaction and 3D Soft-tissue Effects of Mandibular Midline Distraction and Surgically Assisted Rapid Maxillary Expansion	2019	1.0
- AÇBİD Webinar COVID-19, *Zoom meeting* - Impact of COVID-19 on elective surgery and outpatient care. An overview from Rotterdam, the Netherlands	2020	1.0
(Inter)national conferences		
- National conference of the Dutch Society of Oral and Maxillofacial Surgery (NVMKA) - Voorjaars- en Najaarsvergadering	2015-2022	8.0
- IAOMS-AÇBID Joint Congress, Antalya, Turkey	2018	1.0
- 101st AAOMS Annual Meeting, Boston, Massachusetts, USA	2019	1.0
- AÇBİD Webinar COVID-19, *Zoom meeting*	2020	0.5
- WEACADEMY Webinar Genderbevestigende Gelaatschirurgie	2022	0.5
Other		
- Organisatie en bijwonen ‘Research meetings Department of Oral and Maxillofacial Surgery’	2017-2021	3.0

2. Teaching

	Year	**Workload (Hours/ECTS)**
Lecturing		
- Weekly seminars for medical and dental students	2017-2021	2.0
Supervising practicals and excursions, Tutoring		
- Supervising medical and dental students in the outpatient clinic and operation theatre	2017-2021	10.0
Supervising Master’s theses		
- K.R.R. Ramdat Misier	2021	10.0
Other		
- Advisory AIOS-member - Registratiecommissie Tandheelkundige Specialismen (RTS)	2019-2021	3.0
- Board member Werkgroep Esthetische Aangezichtschirurgie (WEAC-NVMKA)	2021-present	1.0

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DANKWOORD

DANKWOORD

Mijn dankwoord gaat allereerst uit naar alle betrokken patiënten binnen dit proefschrift. Ik realiseer mijzelf al te goed dat zonder hun bereidwilligheid dit proefschrift niet tot stand was gekomen. Daarnaast hebben veel waardevolle mensen bijgedragen aan dit proefschrift en daarmee ook aan mijn loopbaan. Een aantal van hen wil ik hieronder in het bijzonder bedanken.

Maarten Koudstaal

Beste Maarten, mijn copromotor, uiteraard begin ik eerst met jou in mijn dankwoord. Als Minor student Geneeskunde heb ik voor het eerst kennis kunnen maken met je. Inmiddels zijn we ruim 11 jaar verder, en wat is er veel gebeurd door de jaren heen. Je bent de reden geweest dat ik dit specialisme heb kunnen ambiëren, en de nodige kansen heb je mij hiervoor aangeboden. Je hebt me letterlijk vanuit blanco opgeleid, zowel wetenschappelijk als klinisch. Mijn oneindige dank daarvoor. Je betekent veel voor mij, en dat zal ook zo blijven. Inmiddels ben ik een collega van je op dezelfde afdeling, hoe geweldig. Ik kijk uit naar nog een jarenlange samenwerking Maarten.

Eppo Wolvius

Beste Professor, mijn promotor, het is eindelijk zover. Het boek is af. Het heeft wat jaren gekost. Als student Geneeskunde ermee begonnen en nu inmiddels staf MKA-chirurg op uw afdeling, maar we zijn er. In dit traject heb ik altijd mijn bewondering gehad hoe snel en adequaat u doorgaans op mijn artikel of mail reageerde, naast al uw bezigheden. U was en bent van het snel doorpakken, een eigenschap die ik zal proberen na te streven. Bedankt voor al uw tijd en inspanning voor dit proefschrift, maar uiteraard ook mijn oneindige dank dat u mij heeft opgeleid tot specialist en nu ook de mogelijkheid heeft gegeven dat ik aansluitend mijn fellowship Hoofd-Halschirurgie mag volgen. Uw afdeling was altijd een warme thuisbasis voor mij, en dat zal ook zo blijven.

Leescommissie

Geachte leden van de leescommissie, Prof.dr. A.G. Becking, Prof.dr. D. Eygendaal en Prof. dr. G.J. Kleinrensink. Hartelijk bedankt voor het beoordelen van mijn proefschrift.

Pieter de Gijt

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ABOUT THE AUTHOR

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Atilla Gül was born in Amsterdam on June 22th, 1988 and grew up in Amsterdam-North with his parents and brother. He attended secondary school at the Bredero College in Amsterdam-North and obtained his VWO diploma in 2006. He started with the study Pharmacy at the University of Utrecht in 2006. One year later he switched to Architecture at the Technical University in Delft. Still pursuing the dream of becoming a doctor, in 2008 he started his Medical training at the Erasmus MC, University Medical Center Rotterdam, the Netherlands. During the Minor program he came in touch with the Department of Oral and Maxillofacial Surgery via dr. Maarten Koudstaal. During his Master, he started with conducting the work described in this thesis (under supervision of dr. Maarten Koudstaal). After obtaining his Medical degree in 2015, he started his Dentistry training at the Radboud University in Nijmegen in 2015, which he completed in 2018. In the same year, he officially started as a resident in training at the Department of Oral and Maxillofacial Surgery at the Erasmus MC, University Medical Center Rotterdam, the Netherlands during 3.5 years (under supervision of Prof.dr. E.B. Wolvius) and the Elisabeth-TweeSteden Hospital, Tilburg, the Netherlands during 6 months (under supervision of J.P.O. Scheerlinck). He finished his residency in 2021 and is currently working as a Staff Member and Fellow Head and Neck Surgery in the Erasmus MC, University Medical Center Rotterdam, the Netherlands. In addition, as of November 2022, he joined the Oral and Maxillofacial Surgery partnership in the Elisabeth-TweeSteden Hospital, Tilburg, the Netherlands.

Atilla lives with his fiancée Kimberly in Rotterdam, the Netherlands.