3D Evaluation of tooth-borne and bone-borne surgically assisted rapid maxillary expansion

Rania Mohamed Nada
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3D Evaluation of tooth-borne and bone-borne surgically assisted rapid maxillary expansion

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door

Rania Mohamed Nada
geboren op 23 maart 1976
te Caïro, Egypte
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Doctoral Thesis

to obtain the degree of doctor
from Radboud University Nijmegen
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according to the decision of the Council of Deans
to be defended in public on Tuesday, February 19, 2013
at 10.30 hours

by

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Chapter 1

General introduction
1.1 Distraction osteogenesis

Bone lengthening by distraction osteogenesis (DO) is nowadays a viable treatment option in the correction of many craniofacial deformities like cleft lip and palate, hemifacial microsomia and transverse jaw discrepancies. DO can be viewed as an endogenous form of tissue engineering as the biological principle is based on the ability of new bone formation between two bone segments that are gradually separated by incremental traction. This process of bone regeneration begins when a distraction force is applied to the healing callus that joins the divided bone segments and continues as long as the tissues are stretched. The development of DO in our modern literature was based on the extensive work of Ilizarov.\textsuperscript{1,2} His classical series of dog experiments not only described the biological principles of DO but also identified the physiological and biomechanical parameters governing its success (Fig. 1).

![Fig. 1 Biomechanical parameters of DO](image)

These factors included the duration of the latency period (time from osteotomy to the start of distraction), the rate of distraction (amount of elongation per/day), rhythm or frequency of distraction (number of distractor activations/day) and the consolidation period (length of time in rigid fixation).

Following the success of DO in the orthopaedic field, the DO principle was successfully applied to the craniofacial complex for the first time by Snyder et al. in 1973.\textsuperscript{3} Later on, the work of McCarthy et al.\textsuperscript{4} Molina and Ortiz-Monasterio\textsuperscript{5} and many others has led to the introduction and recognition of this technique for the treatment of congenital craniofacial anomalies. Over the last two decades, a rapidly
growing number of publications has discussed the applications of DO, various distraction devices, osteotomy designs, factors that could enhance the quality of the distracted bone to shorten the treatment period and possible complications of the technique. Nevertheless, when Swennen et al.\textsuperscript{6} reviewed the literature dealing with DO of the craniofacial skeleton they found very few long-term studies and lack of appropriate data on the long-term treatment effects of DO in terms of relapse and growth potential of distracted tissue.\textsuperscript{6,7} In 2002 Shaw et al.\textsuperscript{8} published a critical appraisal of 88 publications on DO over the period 1995-2000. Nearly all publications were retrospective short-term evaluations of small numbers of cases taken from heterogeneous patient populations without any controls. Given these circumstances, an alternative research approach was proposed: analysis of distraction cases enrolled in a prospective registry. This marked the start of the Eurocran Distraction Study. The study was designed as a multicenter clinical study, consisting of two parts. Part I was a web based survey of the practice of DO in Europe and part II was a prospective registry of patients treated with DO in fourteen clinical centers in Europe. Patients with various conditions like transverse maxillary hypoplasia, cleft lip and palate, unilateral or bilateral mandibular deficiency and bi-maxillary facial deficiency were prospectively enrolled in the study and added to the registry. Using this approach a considerable number of cases could be collected to investigate the short and middle term results of DO. The preliminary results showed that DO of the craniofacial skeleton was considered as an accepted treatment procedure for congenital disorders while evidence was still lacking for the effectiveness of distraction osteogenesis for developmental and acquired craniofacial anomalies.

1.2 Surgically assisted rapid maxillary expansion

Transverse maxillary hypoplasia is a skeletal discrepancy frequently encountered in non-syndromic and syndromic patients and very often combined with a simultaneous vertical or antero-posterior skeletal discrepancy. In clinical practice, skeletal correction of this transverse
discrepancy by orthodontic means alone is only successful before skeletal maturity, i.e. before closure of the mid-palatal suture around the age of 14-16 years in girls and 16-18 years in boys. After this age, orthodontic widening with rapid maxillary expansion (RME) becomes less advisable. With advancing maturity, the rigidity of the skeletal components limits the extent of expansion causing unwanted effects such as tipping of posterior teeth, fenestration of the buccal cortex and above all unstable expansion. For these reasons, orthodontists and maxillofacial surgeons have resorted to the principles of DO in surgically assisted rapid maxillary expansion (SARME) to widen the maxilla and correct substantial posterior crossbites in skeletally mature patients. This treatment is a combination of surgical and orthodontic procedures. Initially, earlier surgical techniques were limited to midline splitting of the midpalatal suture as it was thought to be the main site of resistance. However, later studies emphasized that the major sites of resistance to expansion were the zygomatic buttresses, the piriform aperture and, the pterygomaxillary junction. Identification of these areas of resistance let to the development of various maxillary osteotomy cuts to overcome the skeletal resistance to expansion. There is however no general agreement in the literature on how many areas of resistance need to be transsected during the surgical procedure. While some advocate an extensive procedure with maximum mobilization, others recommend a more conservative approach with minimal complications. Once the areas of resistance have been loosened by the osteotomies, tooth-borne expansion appliances traditionally used for RME are utilized to apply the forces necessary to expand the maxilla (Fig. 2). Despite the improved stability of SARME compared to RME, side effects as well as relapse are not totally eliminated. Overexpansion has been advocated to compensate for the expected 5-25% relapse tendency. This relapse tendency has been presumably attributed to loss of anchorage or tipping of the anchor teeth and lack of control over the bony segments during the consolidation period.
Fig. 2  SARME with a tooth-borne appliance (Hyrax; Dentaurum, Ispring, Germany)

Fig. 3  SARME with a bone-borne appliance (the transpalatal distractor TPD; Surgi-Tec Bruges, Belgium)
In 1999 Mommaerts introduced a bone-borne transpalatal distractor (TPD) (Surgi-Tec, Bruges, Belgium), where the expansion module was directly fixed to the palatal bone by means of two abutment plates and screws\(^2^9\) (Fig. 3). He presumed that applying the expansion force directly to the bone via a bone-borne appliance would provide more skeletal expansion, less undesired tooth movement and would prevent relapse of the expanded bony segments during consolidation.\(^2^4,2^9,3^0\) Consequently, several bone-borne distractors were introduced in the literature. To name a few: the Dresden distractor,\(^3^1\) the Magdenburg palatal distractor,\(^3^2\) the Rotterdam palatal distractor\(^3^3\) and the smile distractor (TITAMED\(^\text{®}\), Antwerp, Belgium). The perceived advantage of bone-borne devices would be that these devices do not interfere with orthodontic treatment, which therefore could be initiated earlier during the consolidation phase. Furthermore the appliances are recommended in patients with periodontally compromised or missing posterior dentition. On the other hand being fixed to the palatal bone, they are more likely to cause inflammation or ulceration of palatal tissues and require a second surgical intervention under local anaesthesia to remove the device. Despite the growing popularity of bone-borne devices, we found weak evidence in the literature\(^2^9\) to support their assumed advantages over tooth-borne appliances.\(^2^2-2^4\)

Although SARME has been the topic of numerous investigations, the current literature reviews\(^2^2,3^4,3^5\) have shown that there is no consensus on many essential steps of the procedure. The presence of a wide variety of expansion devices and treatment regimes makes it difficult to draw definite conclusions from the literature. Moreover, most studies were performed using dental casts despite the fact that SARME does not only influence the position of the teeth but also the alveolar bone, the hard and soft tissues of the mid-face, the nasal cavity and the soft tissues of the nose.
1.3 Three dimensional imaging

1.3.1 Cone beam computed tomography

Over the last decade, three dimensional (3D) imaging or 3D data acquisition and image reconstruction, such as Cone Beam Computed Tomography (CBCT), stereophotogrammetry, digital dental casts and digital impression using intraoral scanners have enhanced our specialty. CBCT scans have become a well established and valuable tool in the orthodontist’s three dimensional (3D) toolkit. Unlike traditional two dimensional (2D) radiographs, CBCT offers an undistorted view of the skull and the dentition. A single scan not only provides an overlap-free visualization of the skull but also allows detailed evaluation of the maxillofacial structures in thin axial, coronal and sagittal slices. A CBCT scan could be visualized as stack of 2D images or segmented into a 3D model (Fig 4).

**Fig. 4** Different image viewing possibilities of CBCT scans; A, Orthogonal slices, B, segmented 3D CBCT models; C, projection of traditional radiographic views.
While the cross-sectional cuts permit access to the internal morphology of the skeletal structures, the 3D modeling provides a complete view of the facial components and their spatial relationship in 3 planes of space.

Superimposition of 2D serial cephalometric radiographs taken at different time points has been traditionally used by orthodontists to quantitatively and visually assess treatment effects and their stability over a certain time interval. Stable structures described in the literature, such as the anterior cranial bases have been classically used to register and orient the two cephalometric tracings. Nowadays, superimposition of CBCT scans allows a 3D visualization of treatment effects over time. This new method of assessing treatment outcomes has the potential to objectify many controversies in orthodontics.

Similar to cephalometric tracings, 3D models constructed from CBCT scans could be superimposed by registering common stable landmarks or by best fit of stable anatomical regions. Registration of the 3D models is a process of combining two or more images from different time points, each with its own coordinate system into a common coordinate system (Fig. 5). There are many software packages available in the market that can register and superimpose CBCT images and the procedure differs slightly between them. Voxel-based image registration is a recently developed automated registration technique whereby CBCT scans are superimposed by comparing the grey values in a defined volume of interest in two scans to compute the rotation and translation required to align them. Rather than relying on user defined landmarks or constructed surfaces, this process automatically compares the grey values in the two images voxel by voxel in a selected region. Once the two models from different time points are registered, the closest point distances between the superimposed 3D surfaces are computed and represented in color coded maps. The location, magnitude and direction of dental, bone and soft tissue displacements can be clearly identified and quantified on these color coded distance maps. Because of its potential to unravel many controversies in orthodontics, the applications of 3D superimposition are constantly increasing in the literature. Albeit its increasing popularity, the accuracy of the superimposition process itself has not been thoroughly
evaluated. Previous literature mainly focused on the accuracy and reliability of landmark identification, linear and angular measurements on the 3D CBCT\textsuperscript{48-51} but not on the superimposition process itself.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Superimposition of two 3D CBCT models: Two scans taken at different time points are registered in a common coordinate system. The surface differences between the two 3D models are computed and represented in color coded distance maps.}
\end{figure}

\subsection{Stereophotogrammetry}

Stereophotogrammetry is another 3D imaging modality that has gained popularity over the last years. Unlike CBCT, the digital 3D data sets of the face could be acquired rapidly and non-invasively without radiation.\textsuperscript{52} The acquired 3D photograph or digital model of the patient’s face has been proven to be an accurate and realistic documentation of the soft tissues and its applications in daily practice are constantly increasing.\textsuperscript{53} Using surface based registration, it is possible to accurately compare 3D photographs of the same individual at different time points.\textsuperscript{54} The resulting images have been used and reported in the literature to evaluate facial asymmetry,\textsuperscript{55} post operative swelling,\textsuperscript{56} soft tissue volumetric changes following orthognathic surgery,\textsuperscript{57} and changes in the nose volume and shape after rhinoplasty.\textsuperscript{58-60} 3D photographs could be accurately fused to or registered on the reconstructed CBCT.
data. The resulting data set provides clinicians with a precise and photorealistic digital 3D representation of a patient’s face. They are therefore nowadays routinely acquired by orthodontists and/or surgeons for 3D surgical preoperative planning.

1.4 Objectives of the thesis

The scope of this thesis was to use the newly available 3D imaging technology to shed more light on two transverse maxillary distraction techniques namely, bone-borne and tooth-borne distraction from a number of different perspectives. The chief question set out to answer was whether there was a difference in the long term results between bone-borne and tooth-borne distraction. We aimed to get more insight into the dento-alveolar as well as the facial soft tissue changes by means of 3D imaging techniques.

The specific aims were:

- To get more insight into the opinion of the European surgeons and orthodontists on the use of DO for patients with different diagnoses to determine areas of clinical confusion.
- To assess the accuracy and reproducibility of voxel based image registration for the superimposition of 3D CBCT models
- To three dimensionally evaluate the long-term skeletal outcome following tooth-borne and bone-borne SARME using superimposed 3D CBCT models
- To assess the long term soft tissue changes in the orofacial region following tooth-borne and bone-borne SARME and to correlate these soft tissue changes with the underlying hard tissue changes.
- To evaluate the long term effects of bone-borne and tooth-borne SARME on the volume of the nose and nasal airway using 3D imaging and simulation software.
Chapter 1

1.5 Overview of the thesis

Chapter 1 provides a general introduction over DO and SARME, the reasons behind the development of bone-borne devices and the potential benefits of 3D imaging.

In Chapter 2 a web based survey, set out to investigate the current practice of DO in Europe, is described.

In Chapter 3 the accuracy and the reproducibility of superimposition of 3D CBCT models was tested on two different anatomical regions.

The results of a two-group prospective cohort study comparing tooth-borne and bone-borne expansion in individuals with a skeletal transverse maxillary deficiency combined with another skeletal discrepancy that required orthognathic surgical intervention are described in Chapter 4, 5 and 6.

In Chapter 4 the long term skeletal changes following tooth-borne and bone-borne SARME were evaluated using 3D CBCT models.

In Chapter 5 the orofacial soft tissue changes following tooth-borne and bone-borne SARME were three dimensionally evaluated and correlated with the dento-alveolar changes.

In Chapter 6 the volumetric changes in the nose and the nasal airway following SARME were investigated using 3D stereophotogrammetry and CBCT scans.

In Chapter 7 the most noteworthy findings are discussed together with the suggestion for future research.

1.6 References


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Current practice of distraction osteogenesis for craniofacial anomalies in Europe: A web based survey

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Luigi Clauser
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Summary

Aim of the study was to get more insight into the opinion of European surgeons and orthodontists on the use of distraction osteogenesis (DO) for patients with different diagnoses and treatment protocols. A web based survey was set up, showing records of four patients with different conditions: hemifacial microsomia (case 1), bilateral mandibular deficiency (case 2), cleft lip and palate (case 3) and Crouzon syndrome (case 4). Respondents from 181 Eurocleft centres were asked to fill out a questionnaire for each patient. Most of the respondents considered case 1 (80%), case 3 (81%) and case 4 (86%) suitable for DO, while only 31% were considering case 2 for DO. There was lack of consensus among the respondents about many aspects of DO. Out of six different treatment parameters, an acceptable degree of agreement was only seen in two: a latency period of 3-7 days and a distraction rate of 1 mm per day. Furthermore, there was noticeable disagreement on the ideal age for treatment, surgical technique, distraction device, and retention period. Our results showed that there is a wide variety in treatment approaches for craniofacial anomalies in Europe. There is disagreement on essential steps in the distraction procedures.
2.1 Introduction

Distraction osteogenesis (DO) is the process of bone lengthening by gradual mechanical distraction. It was first described in the field of orthopaedics by Codivilla\(^1\) in 1905 but this technique gained its popularity after its development by the extensive work of Illizarov in the 1950s.\(^2,3\) Following the success of DO in the orthopaedic field, the first publication on mandibular DO in man appeared in 1992.\(^4\) Since then, DO developed into daily surgical practice for the treatment of different craniofacial anomalies e.g. craniosynostosis, cleft lip and palate (CLP), hemifacial microsomia (HFM), midface hypoplasia, and transverse discrepancies.\(^5,6\) In 2001 McCarthy \emph{et al.}\(^7\) reported about their 11 years experimental and clinical experience with mandibular DO. They concluded that DO of the craniofacial skeleton can be viewed as an endogenous form of tissue engineering. Its application in craniofacial reconstruction continues to expand and evolve. However, in 2002 Shaw \emph{et al.}\(^8\) published a critical appraisal of 88 publications on DO over the period 1995-2000. Nearly all publications were retrospective short-term evaluations of small numbers of cases taken from heterogeneous patient populations without any controls. Given these circumstances, they proposed an alternative research approach: analysis of distraction cases enrolled in a prospective registry. This marked the start of the Eurocran Distraction Study by the end of 2001, which continued until 2005. It aimed at obtaining more insight into the use of DO and its clinical results. The outcome of this study is important for patients with craniofacial anomalies since surgeons and orthodontists all over the world still struggle with lack of evidence when they have to choose between DO or conventional surgical techniques.

The Eurocran Distraction Study was designed as a clinical study, consisting of two parts. Part I is a web based survey of the practice of DO in Europe and part II is a prospective registry of patients treated with DO in 14 clinical centres in Europe. This article deals with the responses to the web based survey (Part I of the study). The aim of the study was to get more insight into the opinion of European surgeons and orthodontists on the use of DO for patients with different diagnoses.
Furthermore, the study aimed to determine areas of clinical confusion, to direct future research on DO.

2.2 Material and Methods

2.2.1 Design of the study
The website designed for part I of the study was registered as www.eurocran.net with a link to the EUROCRAN parent site www.eurocran.org. The website showed records of four patients with different conditions (Fig. 1).

Fig.1 Opening page of the web based survey on the website www.eurocran.net where pictures of the four different cases are shown.
1. Unilateral mandibular hypoplasia: (HFM).
2. Bilateral mandibular deficiency: severe mandibular hypoplasia (CL II).

The records included intra- and extra-oral photographs, pictures of dental casts, lateral head films combined with cephalometric analyses, and panoramic X-rays. If available, the postero-anterior cephalograms, computed tomography images and models were presented as well.

For each patient, the respondents were asked to fill out a questionnaire. The structure of all questionnaires was the same. Briefly, the respondent was asked whether the presented patient could be considered for DO or not. If the answer was yes, the remaining questions were about the preferred surgical technique, DO device and procedure. In case the respondent did not consider the patient for DO, the subsequent questions were about their reasons not to consider DO. All respondents were asked about their experience with the cases shown, their professional discipline and personal data. Answers were loaded automatically into a database. The questionnaires were piloted on 15 respondents, professional workers in the field but who were not in the Eurocleft group. Revisions were made based on their suggestions and the final questionnaires were available online from June 2003 until January 1, 2007. All registered Eurocleft centres with known email addresses, \( n = 181 \), were invited to participate in this study by e-mail. Reminders were sent after 6, 12, and 18 months. Furthermore, all principal contact persons of the participating Eurocleft centres were contacted by phone. During eight scientific meetings, attention was drawn to the website and participants from Eurocleft centres were asked to fill out the questionnaires on the spot using a notebook computer. All patients shown on the website, signed an informed consent regarding the use of their patient data on the website. The website was protected with a password for patient privacy. To subscribe to the survey, a password was sent to an e-mail address. After
subscription, the survey was activated for further completion of the questionnaires.

2.2.2 Analysis of the data
The data were collected from the online database, duplicate entries were discarded (16 entries) and frequency tables were computed for all questions. Relationships and correlations were calculated by Fisher’s Exact Tests using SPSS 14 for Windows (SPSS Inc., Chicago, USA). All hypotheses were two-side tested.

2.3 Results
From the 181 Eurocleft centres that were asked to participate, the response rate to the four questionnaires was as follows (overall response rate per case between brackets):

Case 1 (HFM): \( n = 60 \) (response rate 33%).
Case 2 (CL II): \( n = 54 \) (response rate 30%).
Case 3 (CLP): \( n = 52 \) (response rate 29%).
Case 4 (Crou): \( n = 49 \) (response rate 27%).

2.3.1 The choice between DO and osteotomy
Table 1 gives an overview of the experience of the correspondents with DO, listed per case. For the majority of the respondents, experience with DO was limited to 10 cases or less.

<table>
<thead>
<tr>
<th>Case 1 HFM</th>
<th>Case 2 CL II</th>
<th>Case 3 CLP</th>
<th>Case 4 Crou</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>%</td>
<td>( n )</td>
<td>%</td>
</tr>
<tr>
<td>No previous experience</td>
<td>11</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>10 or less cases</td>
<td>41</td>
<td>68</td>
<td>27</td>
</tr>
<tr>
<td>11+ cases</td>
<td>8</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Total (% Eurocleft)</td>
<td>60</td>
<td>33</td>
<td>52</td>
</tr>
</tbody>
</table>

\( n = \text{number of respondents.} \)
As could be seen in Table 2, most of the respondents considered case 1 (47/59 = 80%), case 3 (42/52 = 81%) and case 4 (42/59 = 86%) to be suitable for DO, while only 31% respondents considered case 2 for DO.

**Table 2.** Reasons not to consider DO (more answers possible)

<table>
<thead>
<tr>
<th>Reason</th>
<th>Case 1 HFM</th>
<th>Case 2 CL II</th>
<th>Case 3 CLP</th>
<th>Case 4 Crou</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osteotomy with or without genioplasty is easier to perform</td>
<td>4/12 (33%)</td>
<td>3/37 (13%)</td>
<td>4/10 (40%)</td>
<td>2/14 (14%)</td>
</tr>
<tr>
<td>Conventional surgery gives same/better results</td>
<td>9/12 (75%)</td>
<td>22/37 (59%)</td>
<td>2/10 (20%)</td>
<td>2/7 (29%)</td>
</tr>
<tr>
<td>Not enough experience with DO</td>
<td>1/12 (8%)</td>
<td>3/37 (8%)</td>
<td>5/10 (50%)</td>
<td>2/7 (29%)</td>
</tr>
<tr>
<td>DO is too expensive</td>
<td>0/12 (0%)</td>
<td>0/37 (0%)</td>
<td>0/10 (0%)</td>
<td>0/7 (0%)</td>
</tr>
<tr>
<td>DO gives too many complications</td>
<td>2/12 (17%)</td>
<td>4/37 (11%)</td>
<td>0/10 (0%)</td>
<td>0/7 (0%)</td>
</tr>
<tr>
<td>Long-term effects of mandibular DO unknown</td>
<td>3/12 (25%)</td>
<td>6/37 (16%)</td>
<td>0/10 (0%)</td>
<td>0/7 (0%)</td>
</tr>
<tr>
<td>Procedure asks too much patient compliance</td>
<td>2/12 (17%)</td>
<td>5/37 (14%)</td>
<td>1/10 (10%)</td>
<td>1/7 (14%)</td>
</tr>
<tr>
<td>Other</td>
<td>6/12 (50%)</td>
<td>6/37 (16%)</td>
<td>0/10 (0%)</td>
<td>0/7 (0%)</td>
</tr>
</tbody>
</table>

**Case 1 HFM**

- Yes: 47; No: 12

**Case 2 CL II**

- Yes: 17; No: 37

**Case 3 CLP**

- Yes: 42; No: 10

**Case 4 Crou**

- Yes: 42; No: 7

No relationship was found between the respondents’ experience with DO and the choice between DO or osteotomy in the four cases (Fisher’s Exact Test, *P* = 0.30, 0.62, 0.54 and 0.09 for cases 1-4 respectively). The reasons why a certain type of patient was not considered to be a distraction candidate were different in each case. The majority (9/12) of those who did not consider the HFM case for DO had the opinion that conventional surgery gives the same or better results than DO. In the Class II patient, 13 out of the 37 respondents who considered this a non-DO case, had the opinion that conventional
surgical mandibular advancement would be easier to perform than distraction of the mandible for the anterior-posterior correction. The result of conventional surgery was assumed to give the same or a better result. Of the 10 respondents who did not consider the CLP patient a case for DO, the reasons given most often were ‘not enough experience with DO’ or ‘a maxillary osteotomy is easier to perform’. For the Crouzon case, “not enough experience with DO” was the main reason not to perform distraction (4/7).

In the overview of the four cases, the costs (0-20%) and possible complications (0-17%) were not decisive in decisions to discard a DO procedure. The long-term results for DO procedures were also a weak determinant not to choose for this technique (0-25%). Patient compliance is for 14-30% of the respondents decisive in technique selection.

2.3.2 Surgical technique and DO device

Tables 3-6 give an overview of the surgical techniques and the DO devices, which were preferred for the four cases by those respondents who considered these cases for DO. For HFM, 51% of the respondents would consider a ramus osteotomy as the preferred surgical technique.

<table>
<thead>
<tr>
<th>Table 3.</th>
<th>Case 1- (HFM) Surgical techniques and devices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surgical technique (n = 47)</strong></td>
<td>n</td>
</tr>
<tr>
<td>body osteotomy</td>
<td>2</td>
</tr>
<tr>
<td>ramus osteotomy</td>
<td>24</td>
</tr>
<tr>
<td>angle osteotomy</td>
<td>16</td>
</tr>
<tr>
<td>other</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Type of DO device (n = 46)</strong></th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>internal monodirectional</td>
<td>11</td>
<td>24</td>
</tr>
<tr>
<td>internal bidirectional</td>
<td>21</td>
<td>46</td>
</tr>
<tr>
<td>external monodirectional</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>external bidirectional</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>external multidirectional</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>combination external and internal device</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>
Only 28% of the respondents would use a monodirectional device and 70% would prefer to use an internal distractor, either mono- or bidirectional (Table 3). In the case of severe mandibular hypoplasia, there was no agreement about the technique and device (Table 4). For HFM and CL II cases, no relationship was found between the surgeon’s experience and the choice for a certain DO technique or device ($P = 0.14, 0.69$). However, it was noted that the respondents tended to use the same DO technique and device for both cases.

### Table 4.  Case 2 - (CL II) Surgical techniques and devices

<table>
<thead>
<tr>
<th>Surgical technique ($n=18$)</th>
<th>$n$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>body osteotomy</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>ramus osteotomy</td>
<td>6</td>
<td>33</td>
</tr>
<tr>
<td>angle osteotomy</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>other</td>
<td>3</td>
<td>17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of DO device ($n = 17$)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>internal monodirectional</td>
<td>5</td>
<td>29</td>
</tr>
<tr>
<td>internal bidirectional</td>
<td>6</td>
<td>35</td>
</tr>
<tr>
<td>external monodirectional</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>external bidirectional</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>external multidirectional</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>combination external and internal device</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 5.  Case 3 - (CLP) Surgical techniques and devices

<table>
<thead>
<tr>
<th>Surgical technique ($n=43$)</th>
<th>$n$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>complete Le Fort I incl pterygomax disjunction</td>
<td>35</td>
<td>81</td>
</tr>
<tr>
<td>incomplete Le Fort I, no pterygomax disjunction</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>segmental osteotomy</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>other</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of DO device ($n=44$)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>rigid external distraction device (RED)</td>
<td>22</td>
<td>50</td>
</tr>
<tr>
<td>facial mask</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>facial mask and internal distraction device</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>internal distraction device</td>
<td>14</td>
<td>32</td>
</tr>
</tbody>
</table>
For the CLP case, 81% preferred a complete Le Fort I including pterygomaxillary disjunction in combination with a rigid external distraction (RED) device (50%). An internal distraction device was preferred by 32% of the respondents (Table 5).

In case 4 (Crou), a Le Fort III osteotomy was preferred by 61% of the respondents, again in combination with the RED device (Table 6).

Table 6. Case 4 - (Crou) Surgical techniques and devices

<table>
<thead>
<tr>
<th>Surgical technique (n=41)</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>monobloc osteotomy</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>fronto-orbital osteotomy</td>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>fronto-orbital + maxillary osteotomy</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Le Fort II osteomy</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Le Fort III osteomy</td>
<td>25</td>
<td>61</td>
</tr>
<tr>
<td>coronal craniectomy</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>other</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of DO device (n=42)</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>rigid external distraction device (RED)</td>
<td>28</td>
<td>67</td>
</tr>
<tr>
<td>facial mask</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>facial mask and internal distraction device</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>internal distraction device</td>
<td>7</td>
<td>17</td>
</tr>
</tbody>
</table>

2.3.3 DO procedure: ideal age, distraction protocol and retention period

The “ideal age to perform DO” was considered to be between 7 and 14 years by 65%, 50% and 48% of the respondents for HFM, CL II and Crouzon cases respectively (Table 7). While other respondents tended to wait a little longer with DO and selected 15 years and older: 63% for the CLP case, 39% for CL II and 38% for the Crouzon case.

The highest degree of agreement between the respondents was found in their answers regarding the distraction protocol. Most respondents agreed on a latency period of 3-7 days (82-88%) after placement of the DO device and before active distraction starts. A DO rate of 1 mm/day was found to be used the most (88-92%).

Finally, for the retention period during which the DO device is kept in place after the active distraction period, the respondents tended to
aim for a shorter retention period for mandibular DO when compared with maxillary DO. For cases 1 and 2, 50-56% chose 6-9 weeks of retention. Meanwhile, about 60% favoured 10 or more weeks for the CLP and the Crouzon cases.

### Table 7. Distraction procedure

<table>
<thead>
<tr>
<th>Case 1 HFM</th>
<th>Case 2 CL Il</th>
<th>Case 3 CLP</th>
<th>Case 4 Crou</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>%</td>
<td>n</td>
<td>%</td>
</tr>
<tr>
<td>Ideal age for DO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 7 years</td>
<td>8</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>7-14 years</td>
<td>31</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td>15+ years</td>
<td>9</td>
<td>7</td>
<td>27</td>
</tr>
<tr>
<td>Latency period</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 3 days</td>
<td>6</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3-7 days</td>
<td>42</td>
<td>14</td>
<td>34</td>
</tr>
<tr>
<td>&gt; 7 days</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Distraction rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 mm/day</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>1 mm/day</td>
<td>44</td>
<td>14</td>
<td>35</td>
</tr>
<tr>
<td>&gt;1 mm/day</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Retention period</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 6 weeks</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>6-9 weeks</td>
<td>26</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>10+ weeks</td>
<td>16</td>
<td>4</td>
<td>25</td>
</tr>
</tbody>
</table>

2.4 Discussion

The aim of the study was to get more insight into the opinion of European surgeons and orthodontists, working in different European craniofacial teams, on the use of DO for patients with different diagnoses. The study also aimed to get an insight into their treatment protocols and parameters regarding craniofacial DO. Although it was hoped that the web based approach would elicit a higher response rate than previous comparable studies, the response rate remained rather low. This might be due to the exhaustive nature of the login procedure and the password security. Another explanation might be the size and design of the questionnaires, although pilot testing showed that it took not more than 15 min to score all four cases. In spite of many attempts
to increase the response rate, it remained rather low. Therefore the results of this survey should be interpreted with caution.

There is one earlier report in which a comparable approach was used. Mofid *et al.*\(^{10}\) studied DO by sending a questionnaire to 2476 craniofacial and oral-/maxillofacial surgeons throughout the world, asking about their experiences of DO. Their response rate was only 11.4%. This study suggests that it is a review of 3278 distraction cases. In fact, it only reflects the experience of 145 surgeons who treated a total of 3278 cases with a wide variety of indications for DO with a main focus on the types of complications encountered with DO. This is somewhat different from our approach, which asked the respondents about their opinion and professional experience in treating specific categories of cases.

The treatment outcome of DO is affected by several clinical parameters which include: age of the patient, surgical technique, distraction device, latency period, distraction rate and retention period. As can be seen from the results of our study, there is lack of consensus among the operators about a lot of aspects of DO. From six different treatment parameters, an acceptable amount of agreement was only seen in two: namely a latency period of 3-7 days, and a distraction rate of 1 mm per day, while there was a noticeable disagreement in the remaining four.

In our study, the majority of the respondents regarded the HFM patient as a suitable case for DO while they regarded the CL II patient to be more easily treated by conventional osteotomy. A recent review by Schreuder *et al.*\(^{11}\) showed some support from the literature for DO having advantages over bilateral sagittal split osteotomy (BSSO) in the surgical treatment of low and normal mandibular plane angle patients who needed greater advancement (>7 mm). In all other mandibular retrognathia patients, the treatment outcomes of DO and BSSO seemed to be comparable. These results could be interpreted that for HFM one would choose DO for the benefit of having bone lengthening with concomitant expansion of the soft tissues on the affected side.\(^{12,13}\) For CL II cases, an osteotomy (with or without chin augmentation) presents a choice of which most of the operators have more years of experience.
On the other hand, the long-term stability of early DO in HFM patients is still a matter of controversy. Whether the presumed soft-tissue expansion from distraction eliminates the need for soft-tissue correction in later stages is also a matter of debate. Mommaerts and Nagy\textsuperscript{14} conducted a literature survey on long-term follow-up of HFM patients treated with early DO. At the time of their survey, they found eight studies, from which only two had more than 10 patients. They concluded from their review that early mandibular DO in HFM corrects the facial asymmetry for a short time. Despite overcorrection, there is relapse of facial asymmetry. The observed effect of DO on the soft tissues was small. Tissue expansion occurred only in the direction of DO and did not result in lateral augmentation. It is not clear whether the recurrence of facial asymmetry after long-term follow-up is due to true relapse of the DO procedure, or relative relapse attributable to the inherent slower growth rate of the affected side.\textsuperscript{15}

The respondents who selected DO for both HFM and CL II cases disagreed on the surgical technique whether it should be a ramus, body or angle osteotomy. They also disagreed on the choice of DO device. This is probably due to the fact that there are many different devices and techniques on the market, while proper testing in large patient groups is still lacking.

It was also obvious in our survey that there is a tendency to differentiate between mandibular DO and maxillary DO in terms of the ideal age of the patient and retention period with overall disagreement on the ideal for each one. Most of the respondents prefer an age of 7-14 years and a retention period of 6-9 weeks for mandibular DO. A slightly higher age (15+ years) and longer retention period (10 or more weeks) were preferred for maxillary DO. On the other hand, a considerable number of respondents, chose to do exactly the opposite i.e. perform mandibular DO for the CL II patient at 15+ years and maxillary DO between 7 and 14 years. The same holds true for the retention period: a noticeable percentage of respondents would apply 10+ weeks for the mandible and a shorter period for the maxilla. A literature review by Swennen \textit{et al.},\textsuperscript{6} in which 430 patients with mandibular lengthening DO and 122 patients with maxillary DO were included, followed a
comparable range for the retention period of 6-8 weeks for the mandible and 9-13 weeks for maxillary DO. For mandibular DO, the majority of patients fell into two age groups: 2-6 years and 7-12 years. For the maxilla, DO was performed at a much younger age (5-13 years) and in Crouzon’s syndrome the midfacial distraction was performed between 4 and 7 years in 36.4% of the patients. While the survey of Mofid et al. did not address the ideal age of the patient, their findings indicated that there was no agreement among the respondents on the length of the retention period, and whether it should vary according to the site of distraction. A recently published meta-analysis on mandibular DO by Ow and Cheung that included 1185 patients treated with DO for mandibular lengthening, showed that at the time of unilateral mandibular DO patients were most commonly aged between 6 and 10 years (28.2%). Patients undergoing bilateral mandibular DO were most commonly younger than 2 years (21.4%), followed by 2- to 5-year-olds (19.3%). Again a consolidation period of 6-8 weeks was most often used in both mandibular DO groups.

For maxillary DO, another recently published review by Cheung and Chua on cleft maxillary osteotomy and DO showed that 45.5% of the documented patients were aged between 16 and 25 years at the time of the osteotomy while 70.65% of the DO patients were aged between 11 and 15 years. The retention period was 2-4 weeks for 36.23% of the patients and 2-3 months in 15.58%. The noticeable variation regarding the age and retention period for maxillary DO found in our results and in other reviews, points to the need for further research on these issues. Regarding the treatment approaches in Europe for the different craniofacial anomalies, our results show that there is a wide variety of treatment approaches with disagreement on essential steps in the distraction procedures. Although the clinical application of DO has a history in long bones, there is still much to learn before the experimental stage of craniofacial distraction can be concluded. A recent search in PubMed revealed that from 2001 until present there are 1095 publications on DO with only four randomized controlled clinical trials and two meta-analyses.
2.5 Conclusion

Based on the existing literature and the wide variation in the European practice revealed in our study, DO of the craniofacial skeleton cannot be considered yet as evidence based care. There are still many unexplained variations in the practice of DO in the craniofacial field that call for a structured collaborative approach using contemporary clinical research designs.

2.6 Acknowledgements

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Chapter 3

Accuracy and Reproducibility of Voxel Based Superimposition of Cone Beam Computed Tomography Models on the Anterior Cranial Base and the Zygomatic Arches

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K. Hero Breuning
Stefaan J. Bergé
Yehya A. Mostafa
Anne Marie Kuijpers-Jagtman

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Abstract

Superimposition of serial Cone Beam Computed Tomography (CBCT) scans has become a valuable tool for three-dimensional (3D) assessment of treatment effects and stability. Voxel based image registration is a newly developed semiautomated technique for superimposition and comparison of two CBCT scans. The accuracy and reproducibility of CBCT superimposition on the anterior cranial base or the zygomatic arches using voxel based image registration was tested in this study. 16 pairs of 3D CBCT models were constructed from pre and post treatment CBCT scans of 16 adult dysgnathic patients. Each pair was registered on the anterior cranial base three times and on the left zygomatic arch twice. Following each superimposition, the mean absolute distances between the 2 models were calculated at 4 regions: anterior cranial base, forehead, left and right zygomatic arches. The mean distances between the models ranged from 0.2 to 0.37 mm (SD 0.08–0.16) for the anterior cranial base registration and from 0.2 to 0.45 mm (SD 0.09–0.27) for the zygomatic arch registration. The mean differences between the two registration zones ranged between 0.12 to 0.19 mm at the 4 regions. Voxel based image registration on both zones could be considered as an accurate and a reproducible method for CBCT superimposition. The left zygomatic arch could be used as a stable structure for the superimposition of smaller field of view CBCT scans where the anterior cranial base is not visible.
3.1 Introduction

Three-dimensional digital records are becoming more and more popular among orthodontists and maxillofacial surgeons as the specialties progress towards a three-dimensional (3D) virtual representation of the patient for diagnosis, treatment planning and simulation. Cone Beam Computed Tomography (CBCT) scans have been well established as a valuable tool in the orthodontist’s and surgeon’s 3D toolkit. A single scan not only provides an overlap-free 3D visualization of the skull but also allows detailed evaluation of the maxillofacial structures in thin axial, coronal and sagittal slices. Superimposition of serial cephalometric radiographs has been traditionally used for assessment of growth and treatment effects or stability over a certain time interval. Nowadays, superimposition of CBCT scans allows a three-dimensional visualization of these effects. Similar to cephalometric tracings, 3D models constructed from CBCT scans could be superimposed manually by registering common stable landmarks or by best fit of stable anatomical regions. These two methods however depend on the accuracy of landmark definition and the precision of the 3D surface models. Voxel-based image registration is a recently developed automated registration technique whereby CBCT scans are superimposed by comparing the grey values in a defined volume of interest in two scans to compute the rotation and translation required to align the two datasets.

Using voxel-based image registration, Cevidanes et al. described the superimposition of CBCT scans on the anterior cranial base structures for both growing and non-growing subjects. They assessed alterations in the 3D position of the mandibular rami and condyles in patients receiving orthognathic surgery. While they demonstrated the reproducibility of this method for CBCT superimposition in the assessment of treatment changes, the accuracy of the superimposition procedure itself at the anterior cranial base was not reported in their studies. Heymann et al. used the same superimposition procedure to determine anatomic changes following maxillary protraction with intermaxillary elastics to miniplates. They concluded that 3D data from CBCT allowed a more thorough documentation of the treatment.
Accuracy and Reproducibility of Voxel Based Superimposition

changes. Another interesting application of voxel based CBCT superimpositions was presented by Swennen et al. They used triple voxel-based rigid registration to build an augmented 3D skull model with detailed occlusal and intercuspation data without the use of plaster dental models.

Despite the growing application of CBCT superimposition to assess changes between serial CBCT scans, neither the accuracy of CBCT scans superimposition techniques nor the choice of structures for 3D superimposition have been directly investigated yet. The anterior cranial base has been traditionally considered as a stable structure for the superimposition of serial two dimensional radiographs. It could be regarded as a stable structure for CBCT superimposition as well. However, this region is only visible in an extended height CBCT scan. It has been shown that reducing the scan height or the Field of View (FOV) from the larger size to the next available smaller size results in a significant reduction, up to 50%, in the radiation dosage to the patient. Many healthcare providers nowadays advocate the use of smaller field of view scans to achieve a balance between what this new technology has to offer to the clinician and the radiation dosage to the patient. The objectives of this study were therefore to evaluate accuracy and reproducibility of a new semi-automated voxel based image registration technique for the superimposition of 3D CBCT models on two different regions, the anterior cranial base and the zygomatic arches as proposed new region for CBCT superimposition in smaller field of view scans.

3.2 Material and Methods

The material for this study consisted of pairs of CBCT scans of 16 adult patients (26±9 yr) retrieved from the Radboud University Nijmegen Medical Centre CBCT database of patients who underwent combined surgical orthodontic treatment. Inclusion criteria were a severe maxillary transverse deficiencies combined with class II or class II malocclusion or open bite, which required two orthognathic surgical interventions. The first CBCT scan was taken prior to treatment while the second was taken
before the second orthognathic surgery, on average 18 (±4.6) months later. The study protocol was approved by the Medical Ethical Commission of the Radboud University Nijmegen Medical Centre, Nijmegen, The Netherlands (181/2005). All patients signed the informed consent. The scans were acquired using the i-CAT® 3D Imaging System (Imaging Sciences International Inc, Hatfield, PA, USA) with a field of view of 22x16 cm and 0.4 mm voxel size. Data from the CBCT were exported in Digital Imaging and Communications in Medicine (DICOM) format to Maxilim software (Medici, Mechelen, Belgium).

### 3.2.1 Superimpositions

3D models were constructed and superimposed using voxel based superimposition in Maxilim software installed on a windows XP-based workstation (Intel® core™ 2 Duo; 2.9 GHz, 3.25GB, ATI Radeon™ 3450 HD graphics card). The construction of the 3D models was performed by selecting the range of grey values representing the bony tissues on the DICOM images. This was achieved by selecting a lower threshold grey value between 250–350.

![Fig. 1 Anatomic structures used for registration highlighted on 3D CBCT models. (A) Anterior cranial base. (B) Left zygomatic arch.](image)

Values above this threshold were automatically selected. The superimposition procedure is an automated procedure that compares the grey values in the two DICOM images voxel by voxel. The user is first required to select the volume of interest (registration area), then to roughly align the 3D models. Consequently the software computes the translation and rotation needed to geometrically align the two DICOM
images, and subsequently the constructed 3D models, based on the maximization of mutual information. For each pair of CBCT scans the 3D model construction and superimposition procedure was repeated five times with a time interval of three weeks.

The scans were registered twice on the anterior cranial base and twice on the left zygomatic arch (zygomatic bone + zygomatic process of the temporal bone) by the same operator (RN) (Fig. 1). To test the inter-observer reliability, the scans were superimposed for a fifth time by a second observer (HB) registered on the anterior cranial base.

![Fig. 2 Transparency overlay of superimposed 3D CBCT models. Right side view. (A) models registered on the anterior cranial base. (B) same models registered on the left zygomatic arch.](image)

![Fig. 3 Transparency overlay of superimposed 3D CBCT models. Frontal view. (A) models registered on the anterior cranial base. (B) same models registered on the left zygomatic arch.](image)
3.2.2 Testing the Accuracy of the Superimpositions

Following each superimposition, using Maxilim software, color coded distance maps as well as transparency overlays were constructed to visualize the superimposed models (Fig. 2, 3, 4 and 5).

**Fig. 4** Transparency overlay of superimposed 3D CBCT models. Left side view. *(A)* models registered on the anterior cranial base. *(B)* same models registered on the left zygomatic arch.

**Fig. 5** Color coded distance maps to visualize treatment changes following two CBCT scans superimposition. The green color indicates that the superimposed model is in front of the original model and red color indicates the opposite. Each color graduation is 1 mm. *(A)* models registered on the anterior cranial base. *(B)* same models registered on the left zygomatic arch.

The mean absolute distances between the two 3D models were computed in 4 different regions: the anterior cranial base, the forehead,
left and right zygomatic arches (Fig. 6 and 7). The absolute values of the distances were exported to excel sheets and the mean value for each region was calculated.

![Distance maps to visualize the distances between two models registered on the anterior cranial base. Color coded distance maps to visualize the distances between two superimposed models registered on the anterior cranial base. The green color indicates that the superimposed model is in front of the original model and red color indicates the opposite. Each color graduation is 0.5 mm. (A) anterior cranial base. (B) the forehead region. (C) the right zygomatic arch. (D) the left zygomatic arch.](image)

**Fig. 6** Distance maps to visualize the distances between two models registered on the anterior cranial base. Color coded distance maps to visualize the distances between two superimposed models registered on the anterior cranial base. The green color indicates that the superimposed model is in front of the original model and red color indicates the opposite. Each color graduation is 0.5 mm. (A) anterior cranial base. (B) the forehead region. (C) the right zygomatic arch. (D) the left zygomatic arch.

### 3.2.3 Statistical Analysis

The intra-observer and inter-observer reliability was calculated using the Pearson correlation coefficient for the mean distances at the 4 anatomical regions following the first and second superimpositions. Paired-sample *t*-test was performed to compare the means of corresponding measurements following registration on the anterior
cranial base and the left zygomatic arch. The significance level was set at 5%.

Fig. 7 Distance maps to visualize the distances between two models registered on the left zygomatic arch. Color coded distance maps to visualize the distances between two superimposed models registered on the left zygomatic arch. The green color indicates that the superimposed model is in front of the original model and red color indicates the opposite. Each color graduation is 0.5 mm. (A) anterior cranial base. (B) the forehead region. (C) the right zygomatic arch. (D) the left zygomatic arch.

3.3 Results

The time required to complete a single superimposition procedure ranged from 30 to 40 min. The mean and standard deviation of the mean distances between the superimposed models at the four regions following the five superimpositions is shown in Table 1.
Table 2 shows the differences between the first and second superimposition on the anterior cranial base. Intra-observer reliability was good between the repeated superimpositions: the correlation coefficients between the first and second superimpositions registered on the anterior cranial base ranged between 0.53 and 0.94 for the mean distances at the 4 regions.

**Table 1.**  Mean distances (mm) between the superimposed models measured at 4 different regions following 5 repeated superimpositions

<table>
<thead>
<tr>
<th>Region</th>
<th>S1 mean</th>
<th>SD</th>
<th>SE</th>
<th>S2 mean</th>
<th>SD</th>
<th>SE</th>
<th>S3 mean</th>
<th>SD</th>
<th>SE</th>
<th>S4 mean</th>
<th>SD</th>
<th>SE</th>
<th>S5 mean</th>
<th>SD</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>0.33</td>
<td>0.12</td>
<td>0.03</td>
<td>0.31</td>
<td>0.07</td>
<td>0.02</td>
<td>0.3</td>
<td>0.12</td>
<td>0.03</td>
<td>0.45</td>
<td>0.22</td>
<td>0.06</td>
<td>0.52</td>
<td>0.35</td>
<td>0.09</td>
</tr>
<tr>
<td>FH</td>
<td>0.2</td>
<td>0.08</td>
<td>0.02</td>
<td>0.19</td>
<td>0.08</td>
<td>0.02</td>
<td>0.13</td>
<td>0.03</td>
<td>0.01</td>
<td>0.39</td>
<td>0.22</td>
<td>0.06</td>
<td>0.35</td>
<td>0.16</td>
<td>0.04</td>
</tr>
<tr>
<td>ZR</td>
<td>0.3</td>
<td>0.24</td>
<td>0.06</td>
<td>0.37</td>
<td>0.31</td>
<td>0.08</td>
<td>0.34</td>
<td>0.25</td>
<td>0.06</td>
<td>0.45</td>
<td>0.27</td>
<td>0.07</td>
<td>0.44</td>
<td>0.21</td>
<td>0.05</td>
</tr>
<tr>
<td>ZL</td>
<td>0.37</td>
<td>0.16</td>
<td>0.05</td>
<td>0.39</td>
<td>0.16</td>
<td>0.04</td>
<td>0.36</td>
<td>0.15</td>
<td>0.04</td>
<td>0.2</td>
<td>0.09</td>
<td>0.02</td>
<td>0.17</td>
<td>0.08</td>
<td>0.02</td>
</tr>
</tbody>
</table>

CB, anterior cranial base; FH, forehead; ZR, right zygomatic arch; ZL, left zygomatic arch; S, superimposition; * superimposition performed by a second observer

**Table 2.**  Mean differences (mm) and 95% confidence interval (CI) between first and second superimposition registered on the anterior cranial base

<table>
<thead>
<tr>
<th>Paired Differences</th>
<th>Mean</th>
<th>SD</th>
<th>SE</th>
<th>Mean</th>
<th>SD</th>
<th>SE</th>
<th>Mean</th>
<th>SD</th>
<th>SE</th>
<th>Mean</th>
<th>SD</th>
<th>SE</th>
<th>Mean</th>
<th>SD</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB.1 - CB.2</td>
<td>0.02</td>
<td>0.09</td>
<td>0.02</td>
<td></td>
<td>-0.03</td>
<td>0.07</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FH.1 - FH.2</td>
<td>0.01</td>
<td>0.07</td>
<td>0.02</td>
<td></td>
<td>-0.03</td>
<td>0.05</td>
<td>0.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZR.1 - ZR.2</td>
<td>-0.07</td>
<td>0.12</td>
<td>0.03</td>
<td></td>
<td>-0.13</td>
<td>-0.003</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZL.1 - ZL.2</td>
<td>-0.01</td>
<td>0.15</td>
<td>0.04</td>
<td></td>
<td>-0.09</td>
<td>0.07</td>
<td>0.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CB, anterior cranial base; FH, forehead; ZR, right zygomatic arch; ZL, left zygomatic arch; S, superimposition; * superimposition performed by a second observer

The interobserver variability was very small when the 3D models construction and superimposition procedure was repeated by a second observer. Mean differences between the superimpositions performed by the first and second observer were 0.02 mm (SD 0.1) for the anterior cranial base, 0.05 mm (SD 0.05) for the forehead region, -0.04 mm (SD...
0.18) for the right zygomatic arch and 0.02 mm (SD 0.14) for the left zygomatic arch.

Table 3 shows the differences between the two superimpositions registered on the zygomatic arches. The correlation coefficients between the first and second superimpositions ranged between 0.24 and 0.71 for the mean distances at the 4 anatomic regions.

**Table 3. Mean differences (mm) and 95% confidence interval (CI) between superimpositions registered on the left zygomatic arch**

<table>
<thead>
<tr>
<th>Paired Differences</th>
<th>Mean</th>
<th>SD</th>
<th>SE Mean</th>
<th>95% CI of the Difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB.4 - CB.5</td>
<td>-0.07</td>
<td>0.25</td>
<td>0.06</td>
<td>-0.2 - 0.06</td>
<td>0.29</td>
</tr>
<tr>
<td>FH.4 - FH.5</td>
<td>0.04</td>
<td>0.24</td>
<td>0.06</td>
<td>-0.1 - 0.18</td>
<td>0.53</td>
</tr>
<tr>
<td>ZR.4 - ZR.5</td>
<td>0.14</td>
<td>0.1</td>
<td>0.05</td>
<td>-0.09 - 0.12</td>
<td>0.78</td>
</tr>
<tr>
<td>ZL.4 - ZL.5</td>
<td>0.04</td>
<td>0.09</td>
<td>0.02</td>
<td>-0.01 - 0.09</td>
<td>0.1</td>
</tr>
</tbody>
</table>

CB, anterior cranial base; FH, forehead; ZR, right zygomatic arch; ZL, left zygomatic arch; 4, fourth superimposition; 5, fifth superimposition; SD, standard deviation; SE, standard error

**Table 4. Mean differences (mm) and 95% confidence interval (CI) between superimpositions registered on the left zygomatic arch and superimpositions registered on the anterior cranial base**

<table>
<thead>
<tr>
<th>Paired Differences</th>
<th>Mean</th>
<th>SD</th>
<th>SE Mean</th>
<th>95% CI of the Difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB.4 - CB.1</td>
<td>0.12</td>
<td>0.19</td>
<td>0.05</td>
<td>0.017 - 0.22</td>
<td>0.025</td>
</tr>
<tr>
<td>FH.4 - FH.1</td>
<td>0.19</td>
<td>0.12</td>
<td>0.05</td>
<td>0.07 - 0.3</td>
<td>0.004</td>
</tr>
<tr>
<td>ZR.4 - ZR.1</td>
<td>0.15</td>
<td>0.18</td>
<td>0.05</td>
<td>0.05 - 0.24</td>
<td>0.005</td>
</tr>
<tr>
<td>ZL.4 - ZL.1</td>
<td>-0.17</td>
<td>0.13</td>
<td>0.03</td>
<td>-0.24 - -0.1</td>
<td>0.001</td>
</tr>
</tbody>
</table>

CB, anterior cranial base; FH, forehead; ZR, right zygomatic arch; ZL, left zygomatic arch; SD, standard deviation; SE, standard error; 4, registered on left zygomatic arch; 1, registered on anterior cranial base

The distances between the superimposed models registered on the zygomatic arch were slightly higher than the models registered on the anterior cranial base at 3 regions (Table 4). The mean differences were 0.12 mm (SD 0.19) for the anterior cranial base, 0.19 mm (SD 0.12) for the forehead region, and 0.15 mm (SD 0.18) for the right zygomatic arch.
On the other hand, the distance between the two models decreased at the left zygomatic arch mean difference was -0.17 mm (SD 0.13). The $P$-values ranged between 0.001 and 0.025 and were statistically significant for the 4 regions.

### 3.4 Discussion

The aim of this study was to test the accuracy and reproducibility of the voxel based superimposition of CBCT scans registered on two different regions: the anterior cranial base and the left zygomatic arch. The accuracy of the superimpositions was tested by calculating the mean absolute distances between the two models at four different anatomic regions: the anterior cranial base, the forehead, the left and the right zygomatic arches. These four regions could be considered as stable structures following orthognathic surgery. The cranial base region was chosen to test alignment errors in the vertical direction, the forehead region for the antero-posterior direction, while the right and left zygomatic arches were chosen for the transverse direction.

To be suitable for routine application in medical image processing, a superimposition procedure should be precise, efficient and should not require an excessive amount of time. The image-analysis procedures used in this study required 30–40 min per set of 2 CBCT scans. This included construction of 3D models, voxel based superimposition of the models, calculation of the distances between the 3D surfaces and generation of color coded distance maps. To our knowledge this required much less time than the procedures reported in previous studies.\(^{10}\) When the models were registered on the anterior cranial base, the average distance calculated between the models ranged between 0.2 and 0.37 mm. Moreover, the reproducibility of this method was confirmed by the small differences between the repeated superimpositions on the anterior cranial base. The mean difference between the distances of the first and second superimposition procedures ranged between 0.02 to 0.07 mm at the four anatomic regions. This difference was statistically significant at the right zygomatic
(P = 0.04), but the clinical relevance is negligible because of the very small values.

Cevidan et al. studied the variability between observers in quantification of treatment outcome on color coded distance maps for different anatomic regions on 3D CBCT models registered on the anterior cranial base. They reported an inter-examiner range of measurements across anatomic regions equal or less than 0.5 mm. They concluded that the small inter-observer variability could be accounted to the automation of the voxel based registration procedure and its independence from the precision of the 3D surface models. This would be equally applicable to the very small intra-observer and inter-observer variability observed in our study. The mean difference between the superimpositions performed by the two observers ranged between 0.02 and 0.05 mm for the four anatomical regions. It should be noted however, that since the distance maps are constructed on the 3D surface models they could be dependent on the accuracy of the segmentation or the selection of the bone threshold values of these models. While the segmentation procedure in our study was different from the procedure used by Cevidan et al., the results of both studies showed that the potential source of variation due to segmentation was very small.

The zygomatic arches could be considered as stable structures for non-growing patients undergoing single or double jaw surgery. They are clearly visible and easily isolated as a region of interest in CBCT scans. With the growing concern about the radiation dosage from CBCT scans, they could offer an added advantage as they are clearly visible in a scan with smaller field of view (FOV) or reduced scan height (13 cm) compared to the anterior cranial base which requires an extended field of view (22 cm). Ludlow et al. and others, have shown that smaller FOV examinations are associated with significant radiation dose reductions and less tissue radiation especially to the eyes. For the i-CAT machine used in our study, the use of the 13 cm FOV scan results in 50% reduction of the overall radiation dose when compared to the 22 cm scan. When the registration was performed on the left zygomatic arch, the distances between the two superimposed models were slightly
larger at the anterior cranial base, the forehead and the right zygomatic arch but were smaller on the left zygomatic arch when compared to superimpositions registered on the anterior cranial base. The mean difference ranged between 0.12 to 0.19 mm. While these differences were found to be statistically significant they are too small to be considered clinically relevant. The mean distances between the two models registered on the zygomatic arch remained within 0.5 mm accuracy advocated by Hajeer et al. Ideally it would be preferred to register the two models on both the right and left zygomatic arches to increase the accuracy of the superimpositions. However, voxel based superimposition could only be performed on one volume of interest at a time using the commercially available software. Hopefully this would be feasible in the near future.

3.5 Conclusion

Voxel based image registration is an accurate and a reproducible semi-automated technique for superimposition of 3D CBCT models. In non-growing subjects, registration of the superimposed models on the zygomatic arches could be considered as an alternative to the anterior cranial base in smaller FOV scans.

3.6 Acknowledgments

The authors would like to acknowledge Dr. Ewald M. Bronkhorst, biostatistician, Department of Preventive and Curative Dentistry, Radboud University Nijmegen Medical Centre for his statistical advice.

3.7 References

Chapter 4

Three-dimensional prospective evaluation of tooth-borne and bone-borne surgically assisted rapid maxillary expansion

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Piotr S. Fudalej
Thomas J.J. Maal
Stefaan J. Bergé
Yehya A. Mostafa
Anne Marie Kuijpers-Jagtman

Abstract

Aim: To three-dimensionally (3D) assess the long-term effects of tooth-borne and bone-borne surgically assisted rapid maxillary expansion (SARME).

Subjects and methods: This prospective cohort study comprised 45 consecutive skeletally mature nonsyndromic patients with transverse maxillary hypoplasia. In 28 patients, a tooth-borne distractor (Hyrax) was used for expansion, whereas in the remaining 17 a bone-borne distractor (transpalatal distractor, TPD) was used. Cone beam computed tomography (CBCT) scans were performed before treatment (T0) and 22 months later, after fixed appliance treatment (T1). 3D models were constructed from CBCT data and superimposed using voxel-based matching. Distance maps between the superimposed models were computed to evaluate the amount of skeletal changes.

Results: The distance maps of the superimposed models showed positive distances on the right and left posterior alveolar segments of the maxilla indicating lateral expansion. The anterior maxillary region showed negative distances or posterior displacement and remodelling of the anterior alveolar region. There was no statistically significant difference between TPD and Hyrax for the three alveolar segments (p values ranged 0.63-0.81).

Conclusion: Bone-borne and tooth-borne SARME were found to produce comparable results at the end of fixed appliance treatment regarding skeletal changes.
4.1 Introduction

Surgically assisted rapid maxillary expansion (SARME) using tooth-borne or bone-borne distractors is a widely accepted technique for correcting substantial transverse maxillary deficiency in adult patients. In these patients, orthodontic treatment alone would result in dental expansion without correcting the transversally-constricted skeletal base; therefore, the expansion of narrow maxillary arches is preferably achieved by surgical separation of the maxillary segments. When conventional tooth-anchored devices are used, the mechanical stresses are applied via the teeth, and relapse of the bony segments is difficult to prevent during the consolidation period. Consequently, applying the expansion force directly to the bone via bone-borne expanders was introduced to provide more skeletal expansion, less undesired tooth movement, and to prevent relapse of the expanded bony segments during consolidation. Both techniques have been thoroughly evaluated and questioned in the literature. Nevertheless, only a limited number of studies have directly compared the two techniques with long-term follow-up.

Inherent limitations of two-dimensional (2D) radiography, such as the superimposition of the anatomical structures and difficulties in landmark identification, explain why most of the previous studies relied on dental plaster models. However, plaster casts provide limited information about the skeletal changes in the maxillary region. Advances in medical imaging techniques and three-dimensional (3D) imaging software not only permit the acquisition of an overlay-free image, but also the construction and superimposition of 3D cone beam computed tomography (CBCT) models. Voxel-based image registration is a recently introduced accurate and reproducible semi-automated technique for superimposition of these 3D models. This new technique is being increasingly used to identify different patterns of remodelling following orthognathic surgery and treatment outcomes in the three planes of space. The goals of the present study were to three-dimensionally evaluate the long-term skeletal outcome following tooth-borne and bone-borne SARME using CBCT imaging. The null hypothesis
to be tested was that there was no difference in skeletal outcome between tooth-borne and boneborne SARME.

4.2 Patients and methods

The study was designed as a two-group prospective cohort study. Forty-five consecutive skeletally mature non-syndromic patients (17 males, 28 females) seeking orthodontic treatment at the Department of Orthodontics and Craniofacial Biology of the Radboud University Nijmegen Medical Centre, Nijmegen (the Netherlands), were prospectively included in this study. Inclusion criteria were skeletal maturity, skeletal transverse maxillary deficiency combined with another skeletal discrepancy that required orthognathic surgical intervention, and no developmental deformity. Exclusion criteria were the presence of developmental deformity or absence of more than four teeth in the posterior maxillary arch. The study protocol was approved by the Medical Ethical Commission of the Radboud University Nijmegen Medical Centre, Nijmegen, The Netherlands (181/2005). All patients provided informed consent.

Under general anaesthesia, a Le Fort I osteotomy was performed with midline osteotomy and pterygo-maxillary disjunction. The same surgical procedure was performed in all patients. In 28 patients, a tooth-borne distractor (Hyrax; Dentaurum, Ispring, Germany) was cemented on dental bands fitted on the first premolars and first molars a few days before the operation. In the remaining 17 patients, a bone-borne distractor (the transpalatal distractor, TPD; Surgi-Tec, Bruges, Belgium) was fixed to the palatal bone during the operation by means of two screws at the level of the second premolars. The choice of the type of distractor was made by agreement between the orthodontist and the surgeon. Generally, the periodontal condition of the anchor teeth and the degree of palatal constriction were influential factors in this decision. Following a latency period of 1 week, the appliances were activated at a rate of 1 mm per day. The expansion was carried out until the palatal cusps of the maxillary teeth touched the buccal cusps of the
lower dentition. When the desired amount of expansion was achieved, the distraction device was blocked by inserting a blocking screw in one of the boreholes of the TPD, and left in place for a consolidation period of 3 months. At the end of the consolidation period, the distraction device was replaced by a transpalatal arch on the first molars. Orthodontic treatment using straight wire fixed appliances was initiated 8-10 weeks after the end of active distraction. The mean age at the time of surgical intervention was 29.4 [±10] years for the TPD group and 24.5 [±9] years for the Hyrax group.

For each patient, a CBCT scan was taken prior to treatment (T0), and a second one was taken an average of 22 (±7) months later, after completion of the pre-surgical orthodontic treatment and prior to the second orthognathic intervention (T1). The scans were acquired using the i-CAT® 3D Imaging System (Imaging Sciences International Inc, Hatfield, PA, USA) with a field of view of 22 x 16 cm and a 0.4-mm voxel size. Data from the CBCT were exported in Digital Imaging and Communications in Medicine (DICOM) format. All measurements were performed by one observer who was not directly involved in the treatment, and who was blinded for the type of treatment.

The DICOM files were imported to InVivoDental software (Anatomage, San Jose, California). Using this software, the mandible and the lower dental arch were cropped on the volume-rendered 3D CBCT models to clearly visualize the maxillary dental arch. The width of the maxillary dental arch was measured at T0 and T1 by measuring the interocclusal distances between the cusp tips of the canines, buccal cusp tips of the first and second premolars, and the mesiobuccal cusp tips of the first and second molars (Fig. 1). The amount of expansion at the level of the root apices was measured on coronal slices at the first molars and premolars. The slices were chosen as described by Podesser et al.\textsuperscript{13} For the first molars, the most anterior slice showing the entire palatal root was chosen. For the first premolars, the most anterior slice in which the crown and root could be seen in their entire length was chosen. Two distances were measured at T0 and T1 on the selected slices; namely, the distance between the palatal root apices (Ap-Ap’) and the distance between the buccal cusps visible on the slices (Cb-Cb’) (Fig. 2). Sixteen
randomly selected CBCT scans were measured twice, with a time interval of 2 weeks between measurements, to determine the intra-examiner reliability.

**Fig. 1.** Amount of occlusal expansion measured on the 3D models.

**Fig. 2.** Distances measured on the coronal slice (A) at the level of the first premolars, and (B) at the level of the first molars; $Ap-Ap'$ is the distance between the palatal root apices, and $Cb-Cb'$ is the distance between the buccal cusps visible on the CBCT slice.
The 3D models were constructed, superimposed, and registered on the anterior cranial base using voxel-based superimposition in Maxilim software (Medicim, Mechelen, Belgium). The accuracy of this superimposition technique was tested and thoroughly described in a previous study. Briefly, the segmentation of the 3D models was performed by selecting the range of grey values (HU) representing the bony tissues on the DICOM images. This was achieved by selecting a lower limit threshold value between 250 and 350. Values above this threshold were automatically selected. The superimposition procedure is an automated procedure that compares the grey values in the two DICOM images voxel by voxel in the selected volume of interest (registration area). Consequently, the software computes the translation and rotation needed to geometrically align the two DICOM images, and subsequently the constructed 3D models based on the maximization of mutual information.

Following each superimposition, colour-coded distance maps were constructed to measure the amount of skeletal expansion at the maxillary alveolar level. Two reference landmarks were placed on the frontal view of the skull defined as the most superior aspect of the concavity of the maxillary bone as it joined the zygomatic process. A line extending between these two reference points was plotted from the frontal view to represent the level of the basal bone of the maxilla (Fig. 3). The maxilla was then divided into three segments; the anterior segment, representing the incisor region, and the right and left posterior segments starting from the distal aspect of the right and left canine. The distances between the 3D models at T0 and T1 were computed separately for each segment. The distances were then exported to Microsoft Excel sheets, and the mean value of each segment was calculated.

Statistical analysis was performed using SPSS (Statistical Package Social Sciences 16.0, SPSS Company, Chicago, IL). Descriptive statistics were first calculated to provide a rough outline of the results in addition to box plots. Independent t-test was used to compare the two groups (significance at \( p < 0.05 \)). The Pearson correlation coefficient test was used to test the relationship between the changes in the anterior
maxillary region and initial inter-canine width, and apical and skeletal expansion. Fisher’s exact test was used to determine the difference between the two groups in the number of patients with asymmetrical expansion. The intra-observer reliability for repeated measurements was calculated using the Pearson correlation coefficient and paired sample t-test for the first and second measurements.

Fig. 3. Reference line plotted from the frontal view.

4.3 Results

Forty-five consecutive patients, comprising 17 males and 28 females, were included in this study. In 17 patients, bone-borne expansion was performed using a TPD (mean age at the time of surgical intervention was 29.4 [±10] years), whereas in the remaining 28 patients a tooth-borne expansion was performed using a banded Hyrax (mean age was 24.5 [±9] years). The average time between the CBCT scans taken at T0 and T1 was 22.6 (±6.9) months for the TPD group, and 21.7 (±6.6) months for the Hyrax group.
Table 1 shows the inter-occlusal distances for both groups at T0 and T1, the mean increase in each distance owing to expansion, and the mean difference between the two groups for each measurement. The groups were comparable for all baseline data prior to treatment (p values ranged 0.83-0.17). There were no significant differences in dental arch widths between the two groups after expansion at T1 (p values ranged 0.22-1). The mean expansion in the TPD group was slightly higher than in the Hyrax group for all inter-occlusal distances. The mean differences in expansion between the two groups ranged between 0.27 mm at the second molars, and 1.77mm at the first molars; however, these differences were not statistically significant.

**Table 1.** Inter-occlusal distances measured on 3D CBCT models (mm)

<table>
<thead>
<tr>
<th>Inter-occlusal distance</th>
<th>TPD n = 17</th>
<th>Hyrax n = 28</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canines T0</td>
<td>30.29 (±3.1)</td>
<td>30.88 (±2.0)</td>
<td>-0.59  0.48</td>
</tr>
<tr>
<td>Canines T1</td>
<td>36.05 (±2.3)</td>
<td>34.98 (±2.5)</td>
<td>1.06   0.22</td>
</tr>
<tr>
<td>difference T1-T0</td>
<td>5.75 (±3.1)</td>
<td>4.09 (±1.8)</td>
<td>1.65   0.06</td>
</tr>
<tr>
<td>1st premolars T0</td>
<td>36.77 (±2.4)</td>
<td>37.11 (±2.4)</td>
<td>-0.33  0.7</td>
</tr>
<tr>
<td>1st premolars T1</td>
<td>43.02 (±1.7)</td>
<td>43.29 (±3.0)</td>
<td>-0.26  0.74</td>
</tr>
<tr>
<td>difference T1-T0</td>
<td>6.24 (±2.3)</td>
<td>5.9 (±2.6)</td>
<td>0.33   0.69</td>
</tr>
<tr>
<td>2nd premolars T0</td>
<td>40.79 (±3.3)</td>
<td>41.61 (±3.4)</td>
<td>-0.81  0.45</td>
</tr>
<tr>
<td>2nd premolars T1</td>
<td>47.37 (±3.1)</td>
<td>47.17 (±3.1)</td>
<td>0.19   0.84</td>
</tr>
<tr>
<td>difference T1-T0</td>
<td>6.66 (±2.6)</td>
<td>5.56 (±3.3)</td>
<td>1.1    0.24</td>
</tr>
<tr>
<td>1st Molars T0</td>
<td>45.01 (±4.3)</td>
<td>46.78 (±3.5)</td>
<td>-1.77  0.17</td>
</tr>
<tr>
<td>1st Molars T1</td>
<td>52.15 (±3.4)</td>
<td>52.15 (±3.2)</td>
<td>0.0002 1</td>
</tr>
<tr>
<td>difference T1-T0</td>
<td>7.14 (±3.7)</td>
<td>5.36 (±2.6)</td>
<td>1.77   0.1</td>
</tr>
<tr>
<td>2nd Molars T0</td>
<td>52.12 (±4.1)</td>
<td>51.83 (±3.8)</td>
<td>0.28   0.83</td>
</tr>
<tr>
<td>2nd Molars T1</td>
<td>56.71 (±3.0)</td>
<td>56.15 (±3.4)</td>
<td>0.55   0.59</td>
</tr>
<tr>
<td>difference T1-T0</td>
<td>4.59 (±2.8)</td>
<td>4.31 (±2.4)</td>
<td>0.27   0.74</td>
</tr>
</tbody>
</table>

TPD, Transpalatal Distractor; CI, Confidence Interval; SD, Standard Deviation; Diff, Difference

The mean expansion at the level of the root apices of the first premolars was 5.2 (±3.2)mm for the TPD group, and 4.6 (±2.3)mm for the Hyrax group (Table 2). The mean expansion at the level of the root
apices of the first molars was 4.6 mm (±3) and 4.58 mm (±2.9) for TPD and Hyrax, respectively. Neither of the variables were statistically significantly different between the two groups ($p = 0.9$).

**Table 2.** Coronal and apical expansion measured on the coronal slices (mm)

<table>
<thead>
<tr>
<th></th>
<th>TPD $n = 17$</th>
<th>Hyrax $n = 28$</th>
<th>Mean Diff.</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td></td>
<td>Upper</td>
</tr>
<tr>
<td>1st premolars</td>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Cb-Cb' T0</td>
<td>36.58 (±3.1)</td>
<td>36.63 (±2.54)</td>
<td>-0.04</td>
<td>0.97 -2.13 2.06</td>
</tr>
<tr>
<td>Cb-Cb' T1</td>
<td>43.54 (±1.8)</td>
<td>43.66 (±3.02)</td>
<td>-0.12</td>
<td>0.88 -1.74 1.5</td>
</tr>
<tr>
<td>Difference T1-T0</td>
<td>6.95 (±3.2)</td>
<td>7.03 (±3.5)</td>
<td>-0.08</td>
<td>0.9 -2.43 2.26</td>
</tr>
<tr>
<td>Ap-Ap' T0</td>
<td>31.32 (±4.2)</td>
<td>31.34 (±5.1)</td>
<td>-0.02</td>
<td>0.99 -3.21 3.17</td>
</tr>
<tr>
<td>Ap-Ap' T1</td>
<td>36.56 (±4.2)</td>
<td>35.96 (±5.05)</td>
<td>0.6</td>
<td>0.7 -2.58 3.78</td>
</tr>
<tr>
<td>Difference T1-T0</td>
<td>5.2 (±3.2)</td>
<td>4.6 (±2.3)</td>
<td>0.62</td>
<td>0.35 -0.71 1.96</td>
</tr>
<tr>
<td>1st molars</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cb-Cb' T0</td>
<td>46.83 (±4)</td>
<td>48.6 (±3.7)</td>
<td>-1.77</td>
<td>0.16 -4.27 0.72</td>
</tr>
<tr>
<td>Cb-Cb' T1</td>
<td>53.6 (±3.17)</td>
<td>54.25 (±3.38)</td>
<td>-0.65</td>
<td>0.53 -2.71 1.42</td>
</tr>
<tr>
<td>Difference T1-T0</td>
<td>6.77 (±3.5)</td>
<td>5.64 (±2.9)</td>
<td>1.12</td>
<td>0.28 -0.98 3.22</td>
</tr>
<tr>
<td>Ap-Ap' T0</td>
<td>31.77 (±3.54)</td>
<td>31.48 (±3.75)</td>
<td>0.28</td>
<td>0.8 -2.02 2.59</td>
</tr>
<tr>
<td>Ap-Ap' T1</td>
<td>36.37 (±2.9)</td>
<td>36.06 (±4.36)</td>
<td>0.31</td>
<td>0.78 -1.9 2.52</td>
</tr>
<tr>
<td>Difference T1-T0</td>
<td>4.6 (±3)</td>
<td>4.58 (±2.9)</td>
<td>0.02</td>
<td>0.9 -1.8 1.9</td>
</tr>
</tbody>
</table>

TPD, Transpalatal Distractor; CI, Confidence Interval; SD, Standard Deviation; Diff., Difference; Cb-Cb', the distance between the buccal cusps visible on the slices; Ap-Ap', the distance between the palatal root apices.

The distance maps of the superimposed models showed positive distances on the right and left posterior alveolar segments of the maxilla, indicating lateral displacement of these segments or alveolar expansion. The anterior maxillary region showed negative distances, indicating posterior displacement of the anterior alveolar region following transversal expansion (Fig. 4). Table 3 shows the mean distances between the superimposed models for the three maxillary segments in both groups. The mean difference between the two groups ranged between -0.21 mm and 0.12 mm. This difference was not statistically significant between the TPD and Hyrax groups at the three alveolar segments ($p$ values ranged 0.63-0.81). There was no correlation between the amount of lateral expansion or the initial inter-canine width at T0 and the changes at the anterior maxillary region ($r = 0.28$, $p$...
= 0.63 and \( r = -0.39, \ p \approx 0.15 \), respectively). There was a significant positive correlation \( (r = 0.597, \ p < 0.001) \) between the amount of apical expansion at the first molars and the sum of left and right lateral expansion on the 3D models. Asymmetric posterior expansion with more than 1.5mm difference between left and right expansion was observed in nine patients; three patients from the TPD group (17.6%) and six from the Hyrax group (21.4%). The number of patients with asymmetric expansion was not statistically significantly different between the two groups \( (p = 1.00, \ \text{Fisher’s exact test version of the Chi-Square test}) \).

Regarding the intra-observer reliability of the repeated measurements on the 3D models and the coronal slices, the correlation coefficient between the first and second measurements on the 3D models ranged between 0.75 and 0.99 \( (p \text{ values ranged from 0.0001 to 0.02}) \). For the measurements on the coronal slices, the correlation coefficient ranged between 0.55 and 0.98 \( (p \text{ values ranged from 0.0001 to 0.16}) \).

Fig. 4. Colour-coded distance maps used to visualize the distances between the superimposed models at the three maxillary segments. The green colour indicates that the superimposed model is in front of the original model, and the red colour indicates the opposite. Each colour graduation is 1 mm.
### Table 3. Alveolar expansion on superimposed 3D CBCT models (mm)

<table>
<thead>
<tr>
<th>Segment</th>
<th>TPD n = 17</th>
<th>Hyrax n = 28</th>
<th>Mean Diff.</th>
<th>P value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Segment</td>
<td>1.91 (±0.97)</td>
<td>1.84 (±1)</td>
<td>0.07</td>
<td>0.81</td>
<td>-0.54 - 0.68</td>
</tr>
<tr>
<td>Left Segment</td>
<td>1.69 (±0.78)</td>
<td>1.56 (±1.11)</td>
<td>0.12</td>
<td>0.65</td>
<td>-0.44 - 0.7</td>
</tr>
<tr>
<td>Anterior Segment</td>
<td>-1.35 (±1.53)</td>
<td>-1.14 (±1.2)</td>
<td>-0.21</td>
<td>0.63</td>
<td>-1.12 - 0.7</td>
</tr>
</tbody>
</table>

TPD, Transpalatal Distractor; CI, Confidence Interval; SD, Standard Deviation; Diff, Difference

### 4.4 Discussion

Randomized controlled trials (RCT) are generally considered the gold standard for establishing the efficacy of an intervention. Nevertheless, RCT assessing surgical interventions are often challenging to undertake. Among these challenges are the random allocation of participants, and the masking of surgeons, patients, or other caregivers, which is often difficult or impossible. The present study was a prospective cohort study, which is considered the best alternative study design when an RCT cannot be readily performed. One of the methodological shortcomings of this design is the lack of randomization of patients into two study groups. Nevertheless, baseline data show that the patients in our study were comparable for all the measured parameters, as shown in Tables 1 and 2. It was also impossible to blind the surgeon, patient, or orthodontist to the treatment, but the observer (RN) who performed all measurements was not involved in the patients’ treatment and was blinded for the type of treatment.

Because of the radiation exposure, it was not possible to quantify the amount of skeletal relapse and dental tipping in both groups by acquiring intermediate CBCT scans at the end of expansion and before fixed appliance therapy. The CBCT scans acquired at the end of orthodontic treatment prior to the orthognathic surgery were indicated for planning the second orthognathic intervention, and as such did not result in additional X-ray exposure. In clinical practice, all patients receive fixed appliance therapy following expansion. According to Byloff and Mossaz, the buccal tipping of anchor teeth immediately following
expansion almost entirely relapses during the period of fixed appliance therapy. Intermediate records taken immediately after expansion would only provide information about the amount of immediate expansion and relapse, but not about the final treatment outcome. Accordingly, the changes reported in the present study were the treatment changes after expansion and fixed appliance therapy.

Superimposition of CBCT 3D surface models and the construction of distance maps is considered a valid and reproducible method for 3D assessment of craniofacial structures. Quantifying skeletal changes using distance maps differs from the traditional linear and angular measurements. Rather than quantifying the change in the distance between two anatomical landmarks, the numbers from the distance maps describe the mean change in all surface points located on a specified anatomical region. The numbers, therefore, reflect the direction of displacement or remodelling, and the average change of the whole region.

The distance maps calculated on the superimposed CBCT scans at 22 months post-expansion showed posterior displacement and remodelling in the anterior maxillary region for both types of expansion. To our knowledge, this is the first study to report the changes in the anterior alveolar region of the maxilla following surgically assisted expansion. The remodelling observed in the anterior maxillary region could be attributed to the changes in the dental arch form and the alveolar remodelling to close the created midline space. There was, however, no correlation between this remodelling and the amount of lateral alveolar expansion.

The average surface changes in the posterior maxillary region were comparable between tooth-borne and bone-borne SARME at 22 months post-expansion. These findings agree with the posterior skeletal changes reported by Koudstaal et al. They compared tooth-borne and bone-borne expanders for SARME using dental casts, lateral, and PA radiographs. Records were taken before treatment, after the distraction phase and at 12 months of follow-up. The skeletal changes measured on the PA radiographs were comparable between the two groups after 12 months of follow-up. On the other hand, a study by Landes et al.
comparing bone-borne and tooth-borne expansion found that bone-borne devices led to significantly more transverse skeletal overall expansion, with a maximum in the premolar region and converging to the molars. However, they used multidetector CT scans taken up to 3 months after maxillary expansion as opposed to 22 months in the present study. Laudemann et al.\textsuperscript{7} followed the same group of patients described by Landes et al.\textsuperscript{18} up to 20.5 months post-expansion using 3D dental models. They found no significant differences between the two groups, but observed a tendency for more transverse maxillary expansion with bone-borne appliances, which corresponds with the findings of the present study.

The position of the bone-borne distractor and pterygoid disjunction were shown to affect the ratio between the amount of anterior and posterior expansion, especially with bone-borne expansion. Pinto et al.\textsuperscript{19} reported more anterior expansion when the TPD was placed at the level of the premolars, and no pterygoid disjunction was performed. Matteini and Mommaerts\textsuperscript{8} showed that placing the TPD at the level of the first molars with pterygoid disjunction resulted in a more parallel expansion along the arch. In the present study, the amount of dental expansion increased from the canines to the molars with bone-borne distraction, whereas it tended to be more parallel along the arch with tooth-borne expansion. Since all patients had fixed appliance therapy, it would be difficult to judge this at the dental arch level.

### 4.5 Conclusions

Bone-borne and tooth-borne SARME were found to produce comparable results at the end of fixed appliance treatment with regards to skeletal changes. Superimposition of 3D CBCT models is an effective way of evaluating dentoalveolar changes following treatment.
4.6 Funding

This work was supported by a grant from the Dutch Technology Foundation (STW 10315). R. Nada was funded by the Netherlands Fellowship Program PhD Studies, Netherlands Ministry of Foreign Affairs, and Netherlands Organization for International Cooperation in Higher Education (Nuffic), grant number: NFP-PhD: CF 2916/2006. The sponsors had no role in the study design; in the collection, analysis, and interpretation of data; in the writing of the manuscript; or in the decision to submit the manuscript for publication.

4.7 Acknowledgements

The authors would like to acknowledge Dr. Martien de Koning who operated on all the patients included in this study.

4.8 References


Chapter 5

Three-Dimensional Evaluation of Soft Tissue Changes in the Orofacial Region after Tooth-Borne and Bone-Borne Surgically Assisted Rapid Maxillary Expansion

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Bram van Loon
Thomas J.J. Maal
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Yehya A. Mostafa
Anne Marie Kuijpers-Jagtman
Jan G.J.H. Schols

Clin Oral Investig; accepted
Abstract

Objectives: To three-dimensionally assess soft tissue changes in the orofacial region following tooth-borne and bone-borne surgically-assisted rapid maxillary expansion (SARME).

Materials and Methods: This prospective cohort study included 40 skeletally mature patients with transverse maxillary hypoplasia. A tooth-borne distractor (Hyrax) was used for expansion in 25 patients. In the remaining 15, a bone-borne distractor (Transpalatal Distractor, TPD) was used. Cone beam computed tomography (CBCT) scans were acquired before treatment (T0) and 22 months later (T1). 3D models were constructed from CBCT data and superimposed using voxel-based matching. Distance maps between the superimposed 3D models were computed to evaluate the degree of skeletal and soft tissue changes in the maxillary region.

Results: Distance maps showed negative distances (mean -1.25 (±1.5) mm) in the middle of the upper lip, indicating posterior repositioning of this area. The cheek region showed positive changes (mean 1.66 (±1.1) mm), reflecting the underlying increase in maxillary width. There was no significant difference between the two groups in all measured distances ($p > 0.05$). Retro-positioning of the upper lip accompanied skeletal remodeling in the anterior alveolar region at a mean ratio of 88%, while the cheek region followed 32% of the alveolar expansion.

Conclusion: Soft tissue changes following SARME include posterior repositioning of the upper lip and increased projection of the cheek area. These changes were comparable between bone-borne and tooth-borne appliances.

Clinical Relevance: this study provides clinicians with information over the expected orofacial soft tissue changes following SARME
5.1 Introduction

Surgically assisted rapid maxillary expansion (SARME) is currently used routinely for the treatment of transverse maxillary deficiency in adult patients. Transverse distraction of the surgically separated maxillary halves has been successfully achieved with either tooth-borne appliances, such as Hyrax (Dentaurum, Ispring, Germany), or bone-borne appliances, such as the transpalatal distractor (TPD; Surgi-Tec, Bruges, Belgium). The latter has been introduced to provide more skeletal expansion, less tipping of the dentition, and a more effective stabilization of the bony segments during the consolidation period. The skeletal and dental response following SARME, with either tooth-borne or bone-borne expansion, is widely reported in the literature.

Despite growing attention among clinicians to the effects of various treatment modalities on the overlying soft tissues, limited information is available concerning the soft tissue facial changes following this procedure. Changes in the transverse and antero-posterior dimensions are particularly difficult to assess in conjunction with each other in a two-dimensional image. Lateral cephalograms, which have been the standard view to evaluate soft and hard tissue changes, lack information about the transverse dimension. This made it difficult for previous studies to correlate skeletal changes with soft tissue changes.

Currently available volume-rendered three dimensional (3D) cone beam computed tomography (CBCT) models make it possible to simultaneously evaluate changes in the three planes of space for both soft and hard tissues via a single model. Using these 3D CBCT models, the current investigation would be the first study to simultaneously evaluate soft and hard tissue changes following expansion. Consequently, the present study was carried out to evaluate, in 3D, the long term soft tissue changes in the orofacial region following tooth-borne and bone-borne SARME and to correlate these soft tissue changes with the underlying hard tissue alterations.
5.2 Patients and methods

5.2.1 Subjects
This prospective study included 40 skeletally mature non-syndromic patients seeking orthodontic treatment at the Department of Orthodontics and Craniofacial Biology of the Radboud University Nijmegen Medical Centre, Nijmegen (the Netherlands). Inclusion criteria were skeletal maturity, skeletal transverse maxillary deficiency combined with another skeletal discrepancy requiring orthognathic surgical intervention, and no developmental deformity.

Exclusion criteria were presence of developmental deformity, absence of more than four teeth in the posterior maxillary arch, and lips not being in rest position during the CBCT scan acquisition. Bone-borne expansion was performed using a TPD in 15 patients (7 males, 8 females; mean age at the time of surgical intervention, 30 ±10 years); tooth-borne expansion was performed using a banded Hyrax in 25 patients (6 males, 19 females, mean age, 25.4 ±9 years).

5.2.2 CBCT
An initial CBCT scan was taken prior to treatment (T0) and a second scan was performed 22 ±7 months later after completion of the pre-surgical orthodontic treatment and prior to the second orthognathic intervention (T1). The scans were acquired using the i-CAT® 3D Imaging System (Imaging Sciences International Inc, Hatfield, PA, USA) with a field of view of 22×16 cm and a 0.4 mm voxel size. Data from the CBCT were exported in Digital Imaging and Communications in Medicine (DICOM) format.

The Medical Ethics Committee of Radboud University Nijmegen Medical Centre, Nijmegen, The Netherlands (#181/2005) approved the study protocol. All patients provided informed consent.

5.2.3 Surgical procedure
Osteotomy at the level of Le Fort I with additional midline osteotomy and pterygo-maxillary disjunction was performed under general anesthesia in all patients. In patients treated with Hyrax, the tooth-
borne distractor was cemented with orthodontic bands fitted on the first premolars and first molars several days before the operation. In patients treated with TPD, the device was fixed to the palatal bone during the operation by means of two screws at the level of the second premolars. All patients were operated on by the same surgeon. The choice of type of distractor was made by agreement between the orthodontist and the surgeon. Generally, the periodontal condition of the anchor teeth and the degree of palatal constriction were factors influencing this decision. Following a latency period of one week, the appliances were activated at a rate of 1 mm per day. Expansion was carried out until the palatal cusps of the maxillary teeth touched the buccal cusps of the lower dentition. When the desired amount of expansion was achieved, the distraction device was blocked by inserting a blocking screw in one of the boreholes of the TPD and left in place for a consolidation period of three months. At the end of the consolidation period, the distraction device was replaced by a transpalatal arch on the first molars. Orthodontic treatment using straight wire fixed appliances was initiated 8-10 weeks after the end of active distraction.

5.2.4 Measurements on superimposed 3D CBCT models

3D models were constructed, superimposed and registered on the anterior cranial base using voxel based superimposition in Maxilim software (Medicim, Mechelen, Belgium). The accuracy of this superimposition technique was tested and thoroughly described previously by our group. All measurements were performed by one observer (RN) who was not directly involved in the treatment and was blinded to the type of appliance.

Following each superimposition, color coded distance maps were constructed to measure the amount of skeletal expansion on the maxillary alveolar level. Two reference landmarks were placed on the frontal view of the skull, defined as the most superior aspect of the concavity of the maxillary bone where it joined the zygomatic process. A line extending between these two reference points was plotted from the frontal view to represent the level of the basal bone of the maxilla. The maxilla was then divided into three segments: anterior segment,
representing the incisor region (B-mid), right (B-right), and left (B-left) posterior segments starting from the distal aspect of the right and left canine, respectively. The distances between the 3D models at T0 and T1 were computed separately for each segment. The distances were then exported to Excel spreadsheets and the mean value for each segment was calculated.

To evaluate soft tissue changes, modified 3D cephalometric analysis based on the 3D cephalometric soft tissue analysis of Swennen et al.\textsuperscript{10,11} was performed to outline the soft tissue region of interest on the superimposed models. Table 1 defines soft tissue landmarks used for this analysis. Using six vertical and two horizontal planes, the maxillary soft tissue region was divided into three subregions (Fig. 1):

- Middle region of upper lip (L-mid)
- Right and left lateral regions of upper lip (L-right and L-left)
- Right and left cheek region posterior to the angle of the mouth (C-right and C-left)

\textbf{Fig. 1} Six vertical and two horizontal planes used to divide the maxillary soft tissues into three subregions; L-m, middle region of upper lip (L-mid); L-r & L-l, right and left lateral regions of upper lip (L-right & L-left); C-r & C-l, right and left cheek region posterior to the angle of the mouth (C-right & C-left)
<table>
<thead>
<tr>
<th>Landmarks and planes</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landmarks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cheilion (left)</td>
<td>ch(l)</td>
<td>Left cheilion, point located at the left labial commissure.</td>
</tr>
<tr>
<td>Cheilion (right)</td>
<td>ch(r)</td>
<td>Right cheilion, point located at the right labial commissure.</td>
</tr>
<tr>
<td>Endocanthion (left)</td>
<td>en(l)</td>
<td>Left endocanthion, soft tissue point located at the inner commissure of the left eye fissure.</td>
</tr>
<tr>
<td>Endocanthion (right)</td>
<td>en(r)</td>
<td>Right endocanthion, soft tissue point located at the inner commissure of the right eye fissure.</td>
</tr>
<tr>
<td>Exocanthion (left)</td>
<td>ex(l)</td>
<td>Left exocanthion, soft tissue point located at the outer commissure of the left eye fissure.</td>
</tr>
<tr>
<td>Exocanthion (right)</td>
<td>ex(r)</td>
<td>Right exocanthion, soft tissue point located at the outer commissure of the right eye fissure.</td>
</tr>
<tr>
<td>nostril base (left)</td>
<td>nb(l)</td>
<td>Lowest point of the left nostril</td>
</tr>
<tr>
<td>nostril base (right)</td>
<td>nb(r)</td>
<td>Lowest point of the right nostril</td>
</tr>
<tr>
<td>Pupil reconstructed</td>
<td>p'</td>
<td>Pupil reconstructed point, midpoint between the endocanthi and pupils, located on the level of the exocanthi.</td>
</tr>
<tr>
<td>Subnasale</td>
<td>sn</td>
<td>Subnasale, midpoint on the nasolabial soft tissue contour between the columella crest and the upper lip.</td>
</tr>
<tr>
<td><strong>Planes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal plane</td>
<td></td>
<td>The horizontal (x) 3D Reference Plane is automatically computed as a plane 6.6 degrees below the Cantion - Superaurale line, along the horizontal direction of the natural head position and through the Pupil Reconstructed Point translated 77.2 mm more posteriorly.</td>
</tr>
<tr>
<td>Vertical plane</td>
<td></td>
<td>The vertical (y) 3D Reference Plane is computed as a plane perpendicular to the Horizontal (x) 3D Reference Plane and along the horizontal direction of the natural head position.</td>
</tr>
<tr>
<td>Subnasal plane</td>
<td></td>
<td>A plane through landmark sn and parallel to the horizontal plane.</td>
</tr>
<tr>
<td>Upper lip plane</td>
<td></td>
<td>A plane through landmarks ch(r) and ch(l) and perpendicular to the vertical plane.</td>
</tr>
<tr>
<td>P1 right</td>
<td></td>
<td>A plane through landmark nb(r) and perpendicular to the upper lip plane.</td>
</tr>
<tr>
<td>P1 left</td>
<td></td>
<td>A plane through landmark nb(l) and perpendicular to the upper lip plane.</td>
</tr>
<tr>
<td>P2 right</td>
<td></td>
<td>A plane through landmarks en(r) and ch(r) and perpendicular to the vertical plane.</td>
</tr>
<tr>
<td>P2 left</td>
<td></td>
<td>A plane through landmarks en(l) and ch(l) and perpendicular to the vertical plane.</td>
</tr>
<tr>
<td>P3 right</td>
<td></td>
<td>A plane through landmark ex(r) and perpendicular to the upper lip plane.</td>
</tr>
<tr>
<td>P3 left</td>
<td></td>
<td>A plane through landmark ex(l) and perpendicular to the upper lip plane.</td>
</tr>
</tbody>
</table>

A separate distance map was computed for each subregion of the superimposed models. The distances were then exported to Excel.
spreadsheets and the mean distance between the two surfaces for each subregion was calculated.

5.2.5 Upper incisor inclination
The change in the upper incisors inclination in relation to the palatal plane (PP) (anterior nasal spine – posterior nasal spine) was measured on sagittal slices, using the most median slice showing the entire root and full crown thickness of the most protruded upper central incisor (Fig. 2).

![Fig. 2](image)

*Fig. 2* Upper incisor inclination in relation to the palatal plane, U1/PP. ANS, anterior nasal spine; PNS, posterior nasal spine

5.2.6 Statistical analysis
Statistical analysis was performed using SPSS (Statistical Package Social Sciences 16.0, SPSS Company, Chicago, IL). Descriptive statistics were first calculated to give a rough outline of the results. The two groups were compared using the independent \( t \)-test (significance at \( p < 0.05 \)). Pearson correlation coefficient was used to test the relationship between the alveolar changes in the maxillary region and the overlying
soft tissue changes. Backward regression analysis was used to determine the best combination of variables that could predict the soft tissue changes. A \( p \) value \( \geq 0.1 \) was used as the threshold for removing a variable from the model. The change in the middle part of the upper lip was used as the dependent variable (L-mid) and six independent variables were initially included in the analysis: change in the middle alveolar region (B-mid), age, gender, type of expansion device, total amount of lateral alveolar expansion (B-right + B-left), and change in upper incisor inclination relative to the palatal plane (U1/pp). For changes in the cheek region, the left cheek region was used as dependent variable and six independent variables were included in the initial analysis: change in the left alveolar region (B-left), age, gender, type of expansion device, total amount of alveolar expansion, and the middle part of the upper lip (L-mid).

5.3 Results

5.3.1 Surface change superimposed models

Table 2 shows the mean distances between the superimposed models for the three maxillary alveolar segments and the five soft tissue sub-regions in both groups. The distance maps of the superimposed models showed positive distances on the right and left posterior alveolar segments of the maxilla, indicating lateral displacement of these segments or alveolar expansion. The anterior maxillary region showed negative distances, indicating posterior displacement of the anterior alveolar region following transversal expansion (Fig. 3a). The mean difference between the two groups ranged from -0.22 to -0.06 mm. This difference was not statistically significant between TPD and Hyrax groups at the three alveolar segments (\( p \) values, 0.53–0.84).

The soft tissue changes seen on the superimposed models reflected the underlying dento-alveolar changes (Fig. 3b). The distance maps of the superimposed soft tissues showed positive distances at the C-right and C-Left regions, indicating increased projection of the cheeks with a
mean surface change of 1.13 ±1.2 mm for the Hyrax group and 1.48 ±1.6 mm for the TPD group; again, this change was not significantly different between groups (p value, 0.47). The middle part of the upper lip (L-mid) showed negative distances, indicating retro-positioning of the central part of the lip. Mean surface change was -1.11 ±1.3 mm for the Hyrax group and -1.6 ±1.9 mm for the TPD group. The mean difference between the two groups was 0.45 mm (p value, 0.43). The lateral regions of the upper lip (L-right, L-left) showed less surface changes, ranging from 0.002 ±1.4 to -0.48 ±1.8 mm. Although the magnitude of changes varied between patients, the soft tissue changes followed the same pattern in 39 patients: retro positioning of the central part of the upper lip, a transitional zone with minimal changes in the lateral parts of the upper lip, and increased projection of the cheek region lateral to angle of the mouth.

Table 2. Comparison between TPD and hyrax. Mean (SD) surface changes between T0 and T1 in mm and upper incisor inclination (in degrees)

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean (SD)</th>
<th>Sig. (2-tailed)</th>
<th>Mean Diff.</th>
<th>95% Confidence Interval of Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hyrax</td>
<td>TPD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>n=25</td>
<td>n=15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft Tissue</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-mid</td>
<td>-1.11 (1.3)</td>
<td>-1.6 (1.9)</td>
<td>0.43</td>
<td>0.45</td>
</tr>
<tr>
<td>L-right</td>
<td>0.002 (1.4)</td>
<td>-0.45 (2.3)</td>
<td>0.49</td>
<td>0.45</td>
</tr>
<tr>
<td>L-left</td>
<td>-0.24 (1.4)</td>
<td>-0.48 (1.8)</td>
<td>0.67</td>
<td>0.24</td>
</tr>
<tr>
<td>C-right</td>
<td>1.13 (1.2)</td>
<td>1.48 (1.6)</td>
<td>0.47</td>
<td>-0.35</td>
</tr>
<tr>
<td>C-left</td>
<td>1.12 (1.2)</td>
<td>0.82 (1.6)</td>
<td>0.55</td>
<td>0.29</td>
</tr>
<tr>
<td>Hard Tissue</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-mid</td>
<td>-1.24 (1.2)</td>
<td>-1.12 (1.5)</td>
<td>0.79</td>
<td>-0.12</td>
</tr>
<tr>
<td>B-right</td>
<td>1.91 (1.1)</td>
<td>1.97 (0.9)</td>
<td>0.84</td>
<td>-0.06</td>
</tr>
<tr>
<td>B-left</td>
<td>1.6 (1.2)</td>
<td>1.82 (0.9)</td>
<td>0.53</td>
<td>-0.22</td>
</tr>
<tr>
<td>Upper incisor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U1/pp pre (*)</td>
<td>109.97 (7.9)</td>
<td>112.01 (7.1)</td>
<td>0.52</td>
<td>-2.04</td>
</tr>
<tr>
<td>U1/pp post (*)</td>
<td>107.34 (11.7)</td>
<td>102.72 (7.6)</td>
<td>0.07</td>
<td>4.62</td>
</tr>
</tbody>
</table>

TPD, Transpalatal Distractor; SD, Standard Deviation; Diff, Difference; U1/pp, upper incisor angulation to palatal plane

Given the fact that there was no significant difference between the Hyrax and TPD groups in the independent sample t-test, the data for both groups were combined for further statistical analysis.
Fig. 3  Color coded distance maps to visualize distances between the superimposed models. The green color indicates that the superimposed model is in front of the original model and red color indicates the opposite; each color graduation is 0.8 mm; a, the distance maps at the three maxillary dentoalveolar segments; B-m, B-mid; B-r, B-right; B-l, B-left; b, the distance maps at the three soft tissue subregions for the same patient; L-m, L-mid; L-r, L-right; L-l, L-left; C-r, C-right; C-l, C-left

5.3.2 Correlations and backward linear regression

Pearson’s correlation showed significant positive correlations between alveolar and soft tissue changes (Table 3). While significant, the correlation between the amount of lateral skeletal expansion and the projection of the cheek regions \( r = 0.34, r = 0.5 \) was not as strong as that of the anterior alveolar region and the upper lip \( r = 0.79 \). On the other hand, there was no significant correlation between changes in the upper lip and changes in the upper central incisor inclination \( r = 0.28 \). Table 4 shows the final backward regression models aiming to predict soft tissue changes. For the upper lip changes, four out of the six initially-included independent variables remained in the model. The
amount of upper lip retraction could be explained by the amount of remodeling in the middle alveolar region, the type of device, the change in the upper incisor inclination, and the age of the patient, with 79% contribution ratio. For every 1mm of retraction or remodeling in the middle alveolar region of the maxilla, a 0.88 mm retraction of the central part of the upper lip would be expected. Regarding the type of device, TPD would be expected to result in less retraction of the upper lip. For the cheek region, only two variables remained in the model. Change in the cheek region could be explained by the amount of changes in the lip and the underlying alveolar expansion.

Table 3. Pearson's correlation coefficients between hard and soft tissue changes

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-mid</td>
<td>-1.25</td>
<td>1.55</td>
</tr>
<tr>
<td>B-mid</td>
<td>-1.01</td>
<td>1.49</td>
</tr>
<tr>
<td>correlation</td>
<td>r= 0.79**</td>
<td>p= 0.0001</td>
</tr>
<tr>
<td>C-right</td>
<td>1.27</td>
<td>1.34</td>
</tr>
<tr>
<td>B-right</td>
<td>1.91</td>
<td>1.01</td>
</tr>
<tr>
<td>correlation</td>
<td>r= 0.34*</td>
<td>p= 0.042</td>
</tr>
<tr>
<td>C-left</td>
<td>1.01</td>
<td>1.39</td>
</tr>
<tr>
<td>B-left</td>
<td>1.66</td>
<td>1.11</td>
</tr>
<tr>
<td>correlation</td>
<td>r= 0.5**</td>
<td>p= 0.001</td>
</tr>
<tr>
<td>Change U1/pp</td>
<td>-5.03</td>
<td>9.20</td>
</tr>
<tr>
<td>L-mid</td>
<td>-1.25</td>
<td>1.55</td>
</tr>
<tr>
<td>correlation</td>
<td>r= 0.28</td>
<td>p= 0.08</td>
</tr>
</tbody>
</table>

SD, standard deviation; U1/pp, upper incisor inclination to palatal plane

5.4 Discussion

The objective of this prospective cohort study was to perform 3D evaluation of the orofacial soft tissue changes following SARME and to correlate these changes with the underlying dento-alveolar changes. Berger et al. used serial frontal photographs to measure changes in facial dimensions following orthopedic and surgically assisted rapid maxillary expansion. Due to the inherent limitation of conventional two dimensional photographs, their study was limited to evaluation of transverse and vertical changes in the soft tissues only. Moreover, some of the changes measured from the skeletal landmarks on postero-
anterior radiographs did not coincide with changes measured from corresponding soft tissue landmarks on the frontal photographs. Therefore, they were unable to correlate some of these soft tissue changes with the underlying skeletal expansion.

Ramieri et al. investigated 3D facial soft-tissue responses to bone-borne SARME using laser scanned facial surfaces, 2D lateral cephalograms, and dental plaster models. While their study provided 3D descriptions of the soft tissue changes, it provided limited information about the underlying skeletal alterations as only dental casts were used to evaluate transverse movements.

Voxel based superimposition of 3D surface models constructed from CBCT scans has become a widely used tool to assess treatment effects and their stability over time in three dimensions. Quantifying changes on color-coded distance maps gives a complete overview of the direction and magnitude of changes in the various anatomical structures. The numbers exported from the distance maps describe the direction and the mean change of all surface points located on the defined hard and soft tissue regions. The soft tissue regions evaluated in the present study were limited to the upper lip and cheek region adjacent to the angle of the mouth. The remaining parts of the cheeks were avoided, as these regions might be influenced by changes in patients’ weight over the two-year treatment period. Ideally, we would have liked to include changes in the nose as well. Unfortunately due to a technical problem in the acquisition of earlier CBCT scans, the tip of nose was cut off in many scans, preventing us from evaluating changes in the nose.

The superimposed CBCT scans were taken before treatment and at 22 ± 7 months post-SARME, at the end of pre-surgical orthodontics. The CBCT scans acquired at the end of the presurgical orthodontic stage were indicated for the planning of the second orthognathic intervention and thus did not result in additional radiation exposure. The soft tissue changes reported in this study were therefore the long term results of the combined effects of SARME and orthodontic treatment. Every surgical procedure causes post surgical swelling, and generally it takes a minimum of 4-6 months to eliminate this effect. In clinical practice all
patients receive fixed appliance therapy 8-10 weeks following SARME, which made it difficult to exclusively evaluate the soft tissue changes at the end of active expansion.

The distance maps calculated on the superimposed CBCT scans showed posterior displacement and remodeling in the anterior maxillary region for both expansion types. This remodeling observed in the anterior maxillary region could be attributed to changes in the dental arch form and alveolar remodeling to close the created midline space. There was, however, no correlation between this remodeling and the amount of lateral alveolar expansion. A more detailed evaluation of the amount of occlusal expansion and its correlation with skeletal changes has been thoroughly described in a previous study involving the same patients. A recurring and comparable pattern of soft tissue orofacial changes was seen in both groups. These changes were characterized by slight retropositioning of the central part of the upper lip and increased projection of the cheek region. The correlation between the changes in the anterior alveolar region and the central part of the upper lip was greater than that seen for the right and left alveolar expansion and the increased cheek projection ($r = 0.79$, compared with $r = 0.34-0.5$). These findings partially agree with those reported by Ramieri et al. While they also reported increased projection of the cheek area, they found no evident change of the upper lip. On the other hand, Filho et al. reported a similar tendency for retropositioning of the upper lip following SARME with conventional suturing when compared with SARME with simple V-Y suture. Differences in surgical techniques might explain variations in results between studies.

Retroclination of upper incisors following SARME had been reported in various studies. In the present study, both groups showed increased retroclination of the upper incisors at the end of orthodontic treatment. This change in inclination of the upper incisor, however, did not correlate significantly with changes in the upper lip. Gungor et al. attributed this retroclination to stretching of the gingival fibers between left and right central incisors during expansion. Based on results of the current study, alveolar remodeling in the anterior
maxillary region to close the midline gap could also be a contributing factor.

When backward linear regression was applied to our analysis, gender and amount of transverse alveolar expansion did not seem to significantly influence changes in the upper lip. Moreover, patient age and inclination of the upper incisor appeared to have very small effects. While the central part of the lip closely followed the anterior alveolar changes, the soft tissues in the cheek region only followed 32% of the underlying transverse alveolar expansion. Based on results of regression analysis, the type of device (TPD or Hyrax) did not seem to significantly influence the amount of changes in the cheek region. The use of TPD would be expected to result in less retraction of the upper lip. This might be an effect of the ratio between the amount of anterior and posterior expansion. The position of the distractor and pterygoid disjunction have been shown to affect the ratio between the amount of anterior and posterior expansion, especially with bone-borne expansion. This might explain differences between the two expansion devices. Since CBCT scans included in the present study were acquired at the end of fixed appliance therapy, it is impossible to evaluate the effect of this ratio on the soft tissue response.

Clinicians currently desire more precise information about the effects of various treatment modalities on the overlying soft tissues. With the increasing popularity of computer-assisted surgical planning, quantifying and predicting changes in the soft tissues has become an essential component of these programs. The results of the present study could be used to validate these computer prediction models.

5.5 Conclusion

Orofacial soft tissue changes following SARME with tooth-borne or bone-borne expansion were comparable. Following SARME, slight retro-positioning of the upper lip and increased projection of the cheeks is to
be expected. Retraction of the upper lip accompanied the remodeling in the anterior alveolar region at a mean ratio of 88%.

5.6 Acknowledgements

The authors would like to acknowledge Dr. Martien de Koning, who surgically treated all patients in this study.

5.7 References

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Chapter 6

Volumetric changes of the nose and nasal airway two years after tooth-borne and bone-borne surgically assisted rapid maxillary expansion

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* Both authors contributed equally

Eur J Oral Sci, submitted
Abstract

This study aimed to assess the effects of bone-borne and tooth-borne surgically assisted rapid maxillary expansion (SARME) on the volume of the nose and nasal airway two years post-surgically. Thirty two patients with transverse maxillary hypoplasia were included in this prospective cohort study. In 19 patients, a tooth-borne distractor (Hyrax) was used for expansion, in the remaining 13 a bone-borne distractor (Transpalatal Distractor, TPD) was used. Cone beam computed tomography scans and 3D photographs of the face acquired prior to treatment and 22 ±7 months later were used to evaluate the volume of the nose and nasal airway. Nasal volume increased by 1.01 ± 1.6 % in the Hyrax group and by 2.39 ± 2.4 % in the TPD group. Nasal airway volume increased by 9.7 ± 5.6 % in the Hyrax group and 12.9 ± 12.7 % in the TPD group. The changes in the nose and nasal airway volume between the pre- and post-treatment measurements were statistically significant ($p < 0.05$). The differences between treatment groups were not statistically significant ($p > 0.05$). Twenty-two months after SARME, the increase in the volume of the nose, and nasal airway was comparable between tooth-borne and bone-borne devices.
6.1 Introduction

Surgically assisted rapid maxillary expansion (SARME) has long been used as a method for correction of transverse maxillary deficiency in adult patients. While the procedure aims to expand the constricted maxilla to coordinate the upper and lower arches; the transversal enlargement of the maxillary apical base simultaneously alters the dimensions of the nose and the nasal cavity. The skeletal and dental effects of SARME with either tooth-borne or bone-borne expansion have been thoroughly described in the literature. However, traditional 2D cephalograms provided limited information on the effects of expansion devices on the dimensions of the nose and nasal airway. With the introduction of three dimensional (3D) imaging modalities like 3D-stereophotogrammetry and cone beam computed tomography (CBCT) a more detailed and accurate evaluation of the changes in soft tissues and airway volumes became feasible. Compared with conventional radiography, CBCT allows a more detailed visualization and quantification of the airway space. Consequently, the past few years have seen an increasing number of publications using CBCT for upper airway analysis following maxillary expansion. These studies have mainly investigated the effects of each expansion device separately or focused on the oropharyngeal airway. The effects of tooth-borne and bone-borne SARME on the volume of the nose and the nasal airway have not yet been directly compared.

The aim of the present study was therefore to evaluate the long term effects of bone-borne and tooth-borne SARME on the volume of the nose and nasal airway using 3D imaging software. The null hypothesis to be tested was that the choice of tooth-borne or bone-borne devices does not result in different volumetric changes of the nose and nasal airway.
6.2 Materials and Methods

This study included 32 patients seeking orthodontic treatment at the Department of Orthodontics and Craniofacial Biology of the Radboud University Nijmegen Medical Centre, Nijmegen (the Netherlands). Inclusion criteria were skeletal maturity, skeletal transverse maxillary deficiency combined with another skeletal discrepancy that required orthognathic surgical intervention, and no developmental deformity. Exclusion criteria were presence of developmental deformity, signs of fluid accumulation in the maxillary sinuses on the CBCT images, and absence of more than 4 teeth in the posterior maxillary arch. Nineteen patients underwent tooth-borne expansion, while the remaining 13 patients underwent bone-borne expansion. The study protocol was approved by the Medical Ethics Committee of the Radboud University Nijmegen Medical Centre, Nijmegen, The Netherlands (#181/2005). All patients gave written informed consent.

6.2.1 Surgical Procedure

The same surgical procedure was applied in all patients and was thoroughly described in a previous study. Briefly, osteotomy at the level of Le Fort I with additional midline osteotomy and pterygo-maxillary disjunction was performed under general anesthesia. In 19 patients, a tooth-borne distractor (Hyrax; Dentaurum, Ispring, Germany) was cemented and fitted on orthodontic bands on the first premolars and first molars. In the remaining 13 patients, a bone-borne distractor (the transpalatal distractor TPD; Surgi-Tec, Bruges, Belgium) was fixed to the palatal bone during the operation by means of two screws at the level of the second premolars. The type of distractor used was chosen following agreement between the orthodontist and the surgeon; this decision was generally based on the periodontal condition of the anchor teeth and the degree of palatal constriction. All operations were performed by the same surgeon (MdK). Following a latency period of one week, the appliances were activated at a rate of 1mm per day. The expansion was continued until the palatal cusps of the maxillary teeth touched the buccal cusps of the lower dentition. When the desired expansion was
achieved, the distraction device was blocked by inserting a blocking screw in one of the boreholes of the TPD, and was left in place for a three-month consolidation period. Orthodontic treatment using straight wire fixed appliances was initiated 8-10 weeks after the end of active distraction.

For each patient, CBCT scans and 3D photographs of the face were taken prior to treatment (T0) and 22 ±7 months later, after completion of the pre-surgical orthodontic treatment and prior to the second orthognathic intervention (T1). The CBCT scans were acquired using the i-CAT® 3D Imaging System (Imaging Sciences International Inc, Hatfield, PA, USA) with a field of view of 22×16 cm and 0.4 mm voxel size. Data from the CBCT were exported in Digital Imaging and Communications in Medicine (DICOM) format. A 3D stereophotogrammetrical camera setup with an integrated software program modular system V 1.0 (3dMDface™ System, 3dMD LLC, Atlanta, GA, USA) was used to capture the 3D photographs of the face. All photographs were taken in natural head position and relaxed facial musculature. For further analysis, the captured images were exported as a wavefront object file (.obj) and imported into Maxilim® software version 2.2.2.1 (Medicim NV, Mechelen, Belgium).

6.2.2 Nasal Volume

The volume of the nose was measured as previously described by van Loon et al.16 First, a surface based matching procedure was performed for the pre- and post-treatment photographs (Fig. 1). This was followed by a modified 3D cephalometric analysis of the superimposed photographs to outline the region of the nose for volumetric measurements using the landmarks and planes as depicted in Table 1. This resulted in the matched 3D photographs on a Cartesian coordinate system with the regions of interest lined by various planes. These planes defined the borders of the volume of the nose and were used for further circumscription of the 3D photograph (Fig. 2). Finally, only the nasal regions were left and a virtual volume could be computed. The left and right nasal volumes of the pre- and post-operative 3D photographs were then measured in cubic centimeters (cm³).
Fig. 1  Superimposed pre- and post-expansion 3D photographs. The green color indicates that the post-expansion photograph is in front of the original one and the red color indicates the opposite. Each color gradation is 1 mm.

Fig. 2  Untextured 3D photographs A, landmarks and planes to outline the nasal area; B cropped nasal area.

In addition to the volume, the greater alar cartilage width (AW) was obtained by measuring the distance between the right and left alar
points. All measurements were performed by the same examiner (BvL), who was blinded for the type of device and was not involved in the patient treatment. The duplicate measurement error of this method was reported in a previous publication.  \[16\]

**Table 1.** Definitions of landmarks and planes used based on the 3D cephalometric soft-tissue analysis

<table>
<thead>
<tr>
<th>Landmarks and planes</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landmarks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alare (left)</td>
<td>al(l)</td>
<td>Left alare, most lateral point on the left alar contour.</td>
</tr>
<tr>
<td>Alare (right)</td>
<td>al(r)</td>
<td>Right alare, most lateral point on the right alar contour.</td>
</tr>
<tr>
<td>Cheilion (left)</td>
<td>ch(l)</td>
<td>Left cheilion, point located at the left labial commissure.</td>
</tr>
<tr>
<td>Cheilion (right)</td>
<td>ch(r)</td>
<td>Right cheilion, point located at the right labial commissure.</td>
</tr>
<tr>
<td>Cheilion (middle)</td>
<td>ch(m)</td>
<td>Soft tissue point automatically computed as the midpoint of the right cheilion and left cheilion.</td>
</tr>
<tr>
<td>Endocanthion (left)</td>
<td>en(l)</td>
<td>Left endocanthion, soft tissue point located at the inner commissure of the left eye fissure.</td>
</tr>
<tr>
<td>Endocanthion (right)</td>
<td>en(r)</td>
<td>Right endocanthion, soft tissue point located at the inner commissure of the right eye fissure.</td>
</tr>
<tr>
<td>Exocanthion (left)</td>
<td>ex(l)</td>
<td>Left exocanthion, soft tissue point located at the outer commissure of the left eye fissure.</td>
</tr>
<tr>
<td>Exocanthion (right)</td>
<td>ex(r)</td>
<td>Right exocanthion, soft tissue point located at the outer commissure of the right eye fissure.</td>
</tr>
<tr>
<td>Exocanthion (middle)</td>
<td>ex(m)</td>
<td>Soft tissue point automatically computed as the midpoint of the right exocanthion and left exocanthion.</td>
</tr>
<tr>
<td>Pupil reconstructed</td>
<td>p'</td>
<td>Pupil reconstructed point, midpoint between the endocanthi and pupils, located on the level of the exocanthi.</td>
</tr>
<tr>
<td>Subnasale</td>
<td>sn</td>
<td>Subnasale, midpoint on the nasolabial soft tissue contour between the columella crest and the upper lip.</td>
</tr>
<tr>
<td><strong>Planes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal plane</td>
<td></td>
<td>The horizontal (x) 3D Reference Plane is automatically computed as a plane 6.6 degrees below the Cantion - Superaurale line, along the horizontal direction of the natural head position and through the Pupil Reconstructed Point translated 77.2 mm more posteriorly.</td>
</tr>
<tr>
<td>Vertical plane</td>
<td></td>
<td>The vertical (y) 3D Reference Plane is computed as a plane perpendicular to the Horizontal (x) 3D Reference Plane and along the horizontal direction of the natural head position.</td>
</tr>
<tr>
<td>Median plane</td>
<td></td>
<td>The median (z) 3D Reference Plane is computed through the Pupil Reconstructed Point and as a plane perpendicular to the horizontal (x) and the vertical (y) 3D Reference Planes.</td>
</tr>
<tr>
<td>Posterior nasal plane</td>
<td></td>
<td>A plane through landmarks ex(l), ex(r) and ch(m).</td>
</tr>
<tr>
<td>Upper nasal plane</td>
<td></td>
<td>A plane through landmark ex(m) and parallel to the horizontal plane.</td>
</tr>
<tr>
<td>Lower nasal plane</td>
<td></td>
<td>A plane through landmark sn and parallel to the horizontal plane.</td>
</tr>
<tr>
<td>Lateral left nasal plane</td>
<td></td>
<td>A plane through landmarks en(l) and all(l) and perpendicular to the vertical plane.</td>
</tr>
<tr>
<td>Lateral right nasal plane</td>
<td></td>
<td>A plane through landmarks en(r) and all(r) and perpendicular to the vertical plane.</td>
</tr>
</tbody>
</table>

### 6.2.3 Airway Volume

The nasal airway volume was measured on the CBCT scans using ITK-SNAP open-source software (http://www.itksnap.org). First, a square shaped area of interest was defined to outline the nasal airway on the mid-sagittal slice. The upper anterior corner was defined by soft-tissue
nasion, while the lower posterior border was defined by the posterior nasal spine (Fig. 3).

**Fig. 3** Square shaped area of interest to outline the nasal airway on the mid-sagittal slice; N', soft tissue nasion used to define the upper anterior corner; PNS, posterior nasal spine used to define the lower posterior border.

All axial slices were checked to ensure that the airway was included in the selected area. The nasal airway was then manually segmented by tracing the soft tissue air interface using user-guided 3D active contour.
segmentation in ITK-SNAP. Once the segmentation was completed, the software automatically computed the volume of the nasal airway in cubic centimeters (Fig. 4). The most anterior coronal slice showing the entire palatal root of the first molars was used to measure the distance between the palatal root apices at T0 and T1. All segmentations were performed by the same examiner (RN) who was blinded to the type of device and was not involved in patient treatment. Eleven randomly selected CBCT scans were segmented twice, with a time interval of 2 weeks, to determine the intra-examiner reliability.

Fig. 4 Segmented nasal airway with ITK-SNAP open-source software (http://www.itksnap.org).

6.2.4 Statistical Analysis

Statistical analysis was performed using SPSS (Statistical Package Social Sciences 16.0, SPSS Company, Chicago, IL). Descriptive statistics were first calculated to give a rough outline of the results in addition to box plots. Pre and post-treatment measurements were compared using paired t-test with significance set at $p < 0.05$. Independent t-test was used to compare the two groups (significance at $p < 0.05$). Pearson correlation coefficient test was used to test the relationship between the volumetric soft tissue changes in the nose and the nasal airway. The intra-observer reliability for repeated measurements was calculated by
6.3 Results

The tooth-borne expansion group comprised 19 patients (5 males, 14 females). The mean age at the time of surgical intervention was 24.2 ± 7 years. The bone-borne group included 13 patients (6 males, 7 females) with a mean age of 31.9 ± 10 years. The average time between the CBCT scans taken at T0 and T1 was 21.7 ± 6.6 months for the Hyrax group and 22.6 ± 6.9 months for the TPD group. The amount of expansion at the level of the palatal root apices of the first molars was 5.46 ± 3.3 mm for the hyrax group and 3.4 ± 2.5 mm and the TPD group. This distance was not significantly different between the two groups (p = 0.13). The amount of dental expansion and its correlation to the skeletal changes have been thoroughly described in a previous study involving the same patients.9

6.3.1 Soft tissue changes of the nose
Intra-observer reproducibility of the nasal volume measurements was reported in a previous publication using the same protocol.16 Table 2 shows the nasal volume measured on the 3D photographs for both groups at T0 and T1. Baseline data prior to treatment was comparable between the two treatment groups (p = 0.11). Following expansion, the nasal volume only increased by 1.08 ± 1.62 % in the Hyrax group and by 2.39 ± 2.4 % in the TPD group. These changes were statistically significant between T0 and T1 (p = 0.008). The absolute and percentage increase in volume was slightly higher in the TPD group than in the Hyrax group; however, this difference was not statistically significant between the two groups (p = 0.12).

The alar width had increased in both groups at T1. The mean increase in alar width was 1.2 ± 0.9 mm in the Hyrax group and 1.4 ± 1.5 for the TPD group. There was no significant difference between the two groups (p = 0.7).
6.3.2 Nasal airway changes

Intra-observer reproducibility was high between the repeated segmentations, with a correlation coefficient of 0.93 between the first and second segmentations ($p < 0.001$). There was no statistically significant difference between the first and second measurements (standard error mean = 1.55 cm$^3$, $p = 0.52$).

Table 3 presents the changes in the nasal airway volume and the comparison between the two treatment groups. The airway volume increased by $9.7 \pm 5.6\%$ in the Hyrax group and $12.9 \pm 12.7\%$ in the TPD group, each representing a statistically significant increase between T0 and T1 ($p < 0.001$). The difference between the two treatment groups was not statistically significant ($p = 0.35$). The absolute and percentage changes in the airway volume were not correlated with the volume changes of the nose as measured on the stereophotogrammetric images ($p = 0.41, r = 0.15$).
6.4 Discussion

The present study investigated the changes of the nose and nasal airway volume following bone-borne and tooth-borne expansion about 2 yr after treatment. These volumetric changes were evaluated using CBCT scans and 3D photographs taken before treatment and at the end of presurgical orthodontics ~22 months post-SARME. The scans acquired at the end of the pre-surgical orthodontic stage were required for planning the second orthognathic intervention and thus did not subject the patients to additional X-ray exposure.

During the acquisition of CBCT scans, the temporomandibular joints are sometimes included in the limited FOV at the expense of including the entire nose. Due to this technical limitation, the tip of the nose was cut off in many scans, which prevented us from evaluating the changes in the nose on the CBCT data. Changes in the nose were instead evaluated by means of 3D photographs acquired on the same day. Retrospectively, the mean age of the patients in the TPD group was higher than in the Hyrax group. Since all patients included in the study were skeletally mature, this between-group age difference does not influence the airway changes described herein.

CBCT imaging proved to be a valuable diagnostic tool in the evaluation of airway shape and dimensions.\textsuperscript{10,18} Segmentation or post processing of the DICOM images using third-party software is generally required to allow the 3D visualization and quantification of the airway volume.\textsuperscript{19} This airway segmentation could be carried out either automatically or manually. Automatic segmentation by differentiating the densities between the airway and surrounding soft tissue by a threshold value is significantly faster and is considered more practical.\textsuperscript{20} Nevertheless, variations in the threshold value have been reported to result in different volume measurements.\textsuperscript{20,21} In the present study, segmentation of the airway was carried out manually by tracing the soft tissue air interface using user-guided 3D active contour segmentation in ITK-SNAP.\textsuperscript{17} Despite being more time consuming, manual segmentation offers the advantage of controlling the airway delineation slice by slice and has been shown to be more accurate.\textsuperscript{17,22}
At 22 months post expansion, a statistically significant increase in the nasal airway volume was observed in both groups (9.7 and 12.9 % for tooth-borne and bone-borne expansion, respectively). This increase did not significantly differ between tooth-borne and bone-borne expansion, confirming the null hypothesis. Deeb et al.\textsuperscript{14} similarly used CT data to evaluate changes in nasal volume following bone-borne expansion using the Dresden bone-borne distractor, and reported only a 5.1 % increase of nasal airway volume as opposed to the 12.9 % increase in the present study. This difference between results could be attributed to the method of airway volume quantification, as they estimated the volume based on three cross-sectional areas in the front, middle, and posterior parts of the nose.

The majority of previous studies have relied on acoustic rhinometry (AR) to evaluate the airway volume. Doruk et al.\textsuperscript{23} found significant correlations between airway volume measurements using AR and CT. Compared to the present study, previous studies that used AR to evaluate the airway volume tended to report a larger percent increase in nasal airway volume. Babacan et al.\textsuperscript{24} found a 14.09% increase in nasal volume while Wriedt et al.\textsuperscript{25} reported a 21.2% increase at 6 months following tooth-borne SARME. A long term follow-up study by Seeberger et al.\textsuperscript{26} reported 23.25% enhancement of the nasal volume at 63 months post expansion.

The functional benefit of such increase in volume has not been fully determined in the literature.\textsuperscript{27} Magnusson et al.\textsuperscript{28} evaluated nasal cavity size, airway resistance, and the subjective sensation of nasal obstruction after SARME at 3 and 18 months post expansion. They reported that a subjective improvement in nasal function was not apparent in the total sample, and was only obvious in subjects with an initial nasal obstruction. Furthermore, they found no correlation between the objective increase in nasal cavity and the subjective sensation of improved nasal function.

Many studies have validated the accuracy of 3D stereophotogrammetry in capturing facial morphologic features.\textsuperscript{29-31} Van Loon et al.\textsuperscript{16} proved its applicability for measuring postoperative changes in nasal volumes following rhinoplasty.\textsuperscript{16,32} In the present study,
the changes in the nose volume following expansion were minimal and were not correlated with the increase in nasal airway volume. The posterior region or the nasal airway showed greater dimensional changes than the anterior or soft tissue part of the nose. Similar findings have been previously reported, and were attributed to the nasal anatomy; because of the greater dimensions of the posterior region of the nasal cavity, the smallest amount of transverse expansion leads to a more pronounced change in the volume.

The increase in nasal base width following SARME is an aesthetic concern for many clinicians. In the present study the nasal width increase was limited to 1.2 mm and 1.4 mm in the Hyrax and TPD group, respectively. These findings correspond with the results of previous studies. Berger et al. reported a 2 mm increase in alar width that was maintained one year following tooth-borne expansion. Similarly Ramieri et al. found 1.4 mm increase in alar width one year following bone-borne expansion. From an aesthetic point of view, it would be difficult to judge how this limited increase would be perceived by the patient. There is no established threshold in the literature to determine the lay person’s and a professional’s perception of variations in the nasal width.

6.5 Conclusion

Twenty-two months following SARME, the increase in alar width, volume of the nose, and nasal airway was comparable between tooth-borne and bone-borne devices.

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6.7 References


Chapter 7

General discussion
7.1 The Eurocran distraction study

Over the past years, distraction osteogenesis (DO) has opened new therapeutic perspectives for the treatment of congenital and acquired craniofacial skeletal anomalies. Although many authors have reported on their clinical experience with DO and found it to be a safe and effective way of reconstructing the craniofacial skeleton, the scientific basis for its use in craniofacial reconstruction is rather weak.\(^1\,^2\) However, since skeletal facial deformities form a heterogeneous group of relatively rare conditions, gathering enough data for a randomized clinical trial (RCT) would be rather difficult to undertake. This implies that only large collaborative research conglomerates can gather sufficient data for research into treatment of these conditions. For this reason, the EUROCRAN distraction study was designed as a prospective registry of cases treated with DO in 14 European clinical centres. The EUROCRAN Distraction Study was part of the European Collaboration on Craniofacial Anomalies study which was funded within the EU Framework V program (QLG1-CT-2000-01019).\(^3\) The aim of the EUROCRAN Distraction Study was twofold: to get more insight into the current use of DO for patients with craniofacial anomalies and to investigate the short and middle term results in cases treated with DO.

At the start of this PhD project, a web-based survey was performed into the current use of DO in Europe (Chapter 2). The use of the world-wide-web offered an easy and inexpensive opportunity to reach all the professional workers in medicine and/or dentistry in Europe. It was expected that this approach would elicit a higher response rate than regular questionnaires. Still the response rate remained between 27-33% despite all the efforts to promote the website at eight scientific meetings as well as via email reminders. The results showed that there was a wide variety in treatment approaches for dentofacial and craniofacial anomalies in Europe during the last decade with noticeable disagreement on the ideal age for treatment, surgical technique, distraction device, and retention period. It also pointed out the need for a structured collaborative approach to explain the variations in the practice of DO in the craniofacial field.\(^4\) The Eurocran web based survey
started in 2003, when DO was still in its infancy in Europe and experience with DO in the craniofacial field was limited. All publications about DO at the time were retrospective short-term evaluations of small numbers of cases.\textsuperscript{2} The majority of the respondents at that time had experience with DO limited to 10 cases or less. Since then many more studies have been published with mid-term and a few with long-term results elucidating the advantages and limitations of DO. It would be interesting to repeat the same web-based survey to find out whether the mindset for DO has changed, as many respondents would have certainly acquired more experience and knowledge about the procedure. It would be worthwhile to investigate which aspects of DO are still under debate.

The EUROCRAN prospective registry included records of patient treated with different diagnostic conditions among which transverse maxillary deficiency. During the 4 years of designing and organising the EUROCRAN distraction osteogenesis study, it became evident that performing research on such a heterogeneous group of patients with relatively rare conditions, demands a permanent and structured collaboration of a substantially large group of clinical centres. During the study, the participating centres were asked to adjust the timing and the frequency of their record schedule to the protocol of the study. Despite the initial enthusiasm, after the first year, many centres did not strictly follow the record schedule for their enrolled patients. Furthermore, the intake of new patients significantly decreased, so it became doubtful whether participating centres really enrolled consecutive cases. In the end the number of enrolled patients with complete records for the outcome analysis was disappointing. For these reasons, it was decided to only include patients treated at the Radboud University Nijmegen Medical Centre in the studies presented in this thesis.

Collaboration between surgical research communities is still needed to enable the conduct of appropriate and well-designed trials. This type of collaboration requires a permanent and structured collaboration of a substantially large group of clinical centres. A limited number of years is not sufficient to gather enough data for sound research into aetiology and treatment of these rare conditions. When multiple clinical centres
participate in a research setting for many years, timely implementation of a standard record taking schedule and use of a pre-defined scoring system of evaluation criteria, will inevitably lead to consistency in outcome analysis. Another key element to guarantee the longevity of such collaborations in the future is to maintain a reasonable balance between the desired outcome evaluation and the burden implied by the record taking schedule on the participating centres.

7.2 Methodological considerations

In this section three issues are discussed concerning the methodology of the present study.

Firstly, the study methodology is discussed with respect to the chosen design and blinding procedures (paragraph 7.2.1).

Secondly, the use of CBCT in longitudinal studies with special emphasis on radiation dosage to the patients is considered (paragraph 7.2.2).

Finally, the implications of 3D superimposition techniques with regard to various registration techniques are discussed (paragraph 7.2.3).

7.2.1 Study design

The outcome assessment of any complex surgical intervention is challenged by many factors that depend on the operator, the team and the setting. RCTs are often considered the ideal method for measuring treatment effects. In this study design the compared groups are balanced regarding various types of biases, both known and unknown factors influencing the outcome. Consequently, if a treatment effect is observed there will be more confidence in concluding that one intervention is better than the other. Nevertheless, RCTs are not frequently performed for surgical interventions since it is often difficult to conceal the treatment modality and to randomize the patients into the treatment groups.
The present study was a two-group prospective cohort study which is considered the best alternative study design when an RCT cannot be readily performed.\textsuperscript{8} One of the methodological shortcomings of this design is the lack of randomization of patients into two study groups.\textsuperscript{5,8} The allocation to a study group, whether bone-borne or tooth-borne distraction, was influenced by the palatal morphology and the periodontal conditions of the anchor teeth. Retrospectively, the baseline data showed that the patients in both groups were comparable for all the measured parameters. Nevertheless, in spite of the lack of randomization we strived to eliminate other forms of bias in our study design.

A key consideration in every study design is “blinding”. Blinding refers to the process by which study participants, treating personnel and outcome assessors are kept unaware of the allocated study group.\textsuperscript{9} The extent of which blinding is feasible will depend upon the nature of the interventions and also the outcome under investigation.\textsuperscript{10} Blinding of the surgeon and/or patients for evaluations of surgical techniques is often impossible. In our study it was indeed impossible to blind the surgeon, patient or orthodontist to the type of distraction, but the observers who performed all measurements were not involved in the patients' treatment and were blinded for the type of treatment. As the observers were blinded for the type of treatment this prevented optimism bias or the belief that a new therapy is better than an established one. Such type of bias may influence both investigators and subjects, especially in the evaluation of subjective measurements and can lead to new treatment procedures without scientifically valid evidence.\textsuperscript{11}

Another source of variability that may need to be controlled for in surgical studies is performance bias. It is particularly a problem in surgical studies involving surgeons with varying experience, as a surgeon’s experience can impact the outcome of a given procedure.\textsuperscript{11} To avoid performance bias in the present study, the same surgical and retention protocol was followed in all patients and was performed by the same experienced surgeon.\textsuperscript{11} Therefore within the limits of the present study design, various types of bias that could influence the
evaluated outcome were successfully avoided despite the lack of randomization.

7.2.2 Use of cone beam computed tomography in longitudinal studies

For decades, serial cephalograms taken at different time points have been essential to orthodontists to assess treatment progress and analyze changes due to growth, aging and relapse. Over the past few years, three dimensional (3D) imaging modalities like cone beam computed tomography (CBCT) have boosted our profession by providing a 3D representation of the maxillofacial skeleton with minimal distortion. For the first time, clinicians were not constrained by the predetermined two dimensional (2D) views. Multiplanar reconstructions allow virtually any view to be selected making a significant amount of additional information available to the clinician. Nevertheless, this abundant information came at the cost of increased radiation dosage to the patients.\textsuperscript{12,13} This associated risk has constrained the use of CBCT in longitudinal studies and limited its great potentials to improve treatment outcome assessment, to enhance the interpretation of variations in patient response to treatment, and to eventually settle many controversies in the profession.

As orthodontists are beginning to appreciate the advantages that the third dimension gives to clinical diagnosis and treatment planning, they are at the same time struggling to find a balance between what this new technology has to offer on one hand and the radiation risks to the patient on the other hand. Opinions on the overall use of CBCT in orthodontics range from advocating its routine use for all orthodontic patients, to guidelines on its limited use in specific cases.\textsuperscript{14,15} The latter guidelines recommend the use of CBCT in selected cases in which conventional radiography cannot supply satisfactory diagnostic information. These cases include cleft lip and palate patients, assessment of unerupted tooth position, identification of root resorption caused by unerupted teeth and planning of orthognathic surgery. In these cases its use has been justified as it enhances diagnosis and treatment planning and its benefits seem to exceed the risks.
In this thesis, all patients had skeletal transverse maxillary deficiency combined with an additional skeletal discrepancy and were planned for a second orthognathic intervention. The CBCT scans were acquired before treatment and on average 22 months following surgically assisted rapid maxillary expansion (SARME) at the end of the pre-surgical orthodontics. The scans acquired at the end of orthodontic treatment prior to the orthognathic surgery were indicated for the surgical planning and as such did not result in additional X-ray exposure. Nevertheless, this entailed that the dental and skeletal effects reported in our study are the long term changes following SARME and fixed appliance therapy. Ideally, an intermediate CBCT scan, immediately at the end of expansion and before fixed appliance therapy would have provided more information about the amount of immediate expansion and hence it would have been possible to evaluate the amount of dental tipping and relapse. Unfortunately this scan would have had little clinical benefit to the patient to substantiate the radiation exposure.

### 7.2.3 Superimposition of 3D CBCT models

In this thesis newly available 3D imaging technologies were used to evaluate and compare the long term effects of tooth-borne and bone-borne SARME. The use of 3D imaging in general and CBCT scans specifically aimed at overcoming the limitations of previous studies which relied on 2D radiographs or plaster dental models. While these studies thoroughly described the dental changes measured on dental models, the amount of skeletal changes was often quantified by a couple of linear measurements between two skeletal landmarks on postero-anterior (PA) radiographs. In order to obtain a more detailed evaluation of these skeletal effects, we therefore relied on the superimposition 3D CBCT. Unlike regular superimpositions, the treatment changes are not expressed as differences in angular and linear measurements but as volume and surface changes in a defined region of interest on the superimposed 3D CBCT models. When the surface changes are represented in colour coded distance maps, they provide the clinician with an overview of the magnitude and direction of the changes.
surface changes and consequently reveal areas of bone displacement and remodeling.

There are various CBCT registration techniques reported in the literature and the procedure slightly differs between them.

The simplest registration procedure is done by selecting the same anatomical landmarks in the 2 CBCT images. The software then computes the best fit between these 2 sets of landmarks and relocates one CBCT image relative to the other so that they share the same coordinate system.29 This technique however relies on the accuracy of landmark location on the 3D models and the selection of the same landmark points in the 2 CBCT images.30,31

A second method of CBCT registration is surface to surface registration by using the best fit of two anatomical structures. This approach offers a more precise registration as it uses a surface composed of thousands of landmarks rather than a few user selected landmarks.30 Nevertheless this registration method depends on the precision of the 3D surface model.

A third method of registration and the one used in this thesis is voxel-based image registration. In this recently developed automated registration technique, the CBCT scans are superimposed by comparing the grey values in a defined volume of interest in both scans. Rather than relying on user defined landmarks or constructed surfaces, this process automatically compares the grey values in the two images voxel by voxel in a selected region.32,33 The image-analysis procedures used in our study34 required 30–40 min per set of 2 CBCT scans. To our knowledge this required significantly less time than the procedures reported in previous studies that similarly used voxel based superimposition.32,35-38 The difference between the procedures lies in the segmentation process. In the present study, the 3D models were constructed using automatic segmentation with a threshold value or in other words by selecting the range of grey values representing the bony tissues on the DICOM images. This significantly reduced the time needed for the whole procedure as opposed to manual segmentation used by other research groups. The results in chapter 3 showed that the procedure could be considered as a reliable and reproducible method.
with less than 0.5 mm measurement error.\(^{34}\) However, at the moment, the superimposition procedure remains too elaborate for routine clinical application and is therefore limited to academic research setups. The operator needs to manually perform a number of steps which require a substantial amount of computation time. Hopefully, in the near future developments in the currently available software applications will enable the automation of the segmentation and superimposition processes to render them more clinician-friendly and less time consuming.

### 7.3 Tooth-borne versus bone-borne distraction

#### 7.3.1. Combined skeletal and dental effect

The central question in this study was whether there was a difference in the long term results of tooth-borne and bone-borne distraction. Remodeling of the anterior maxillary segment and lateral expansion of the right and left posterior segment was shown in both groups (Chapter 4). The differences between the two groups were not statistically significant in all the measured parameters, indicating that the long term skeletal effects of both expansion regimes are comparable.\(^{39}\) While this discards the major advantage claimed by the advocates of bone-borne distraction,\(^{16,22,23,40}\) both appliances remain to have their individual advantages and disadvantages. Bone-borne appliances like TPD avoid negative orthodontic effects such as periodontal ligament compression and are therefore optimal to use in a periodontally compromised dentition (fig 1). On the other hand, the necessity for screw fixation when the TPD is placed bears some risks that are avoided with tooth-borne expansion, the most common being ulceration of palatal mucosa, the risk of damaging the underlying roots of the dentition or introducing the burr or screw into the maxillary sinus especially in patients with hypoplastic maxilla.\(^{41}\)
In addition to the expansion appliance, the surgical procedure or the extent of maxillary mobilization is equally believed to influence the outcome of SARME\textsuperscript{18,21,41}. Several modifications of the surgical approach have been recommended to reduce the areas of resistance to lateral expansion in the midface\textsuperscript{18,24}. In the present study, the same surgical procedure was followed in both groups to avoid the influence of the surgical approach. Our surgical procedure consisted of an osteotomy at the Le Fort I level with additional midline osteotomy and pterygo-
maxillary disjunction. Releasing the pterygoid junction is considered surgically more demanding and some surgeons choose to avoid it because of the increased risk of injuring the pterygoid plexus by the osteotomy. However, pterygo-maxillary separation results in a greater degree of mobilization of the maxillary segments and thus increases the expansion of the maxilla while reducing the forces on the anchor teeth. As there is no consensus in the literature on the extent of surgery required to facilitate maxillary expansion, the variations in the surgical approach may possibly account for some of the differences between our findings and those of previous studies.

7.3.2 Effect on the soft tissues
The effects of tooth-borne or bone-borne SARME are not limited to the dentition, the transverse expansion equally affects the overlying soft tissues. Despite growing attention among clinicians to the effects of various treatment modalities on the overlying soft tissues, limited information is available concerning the soft tissue facial changes following this procedure. The use of the volume-rendered 3D CBCT models made it possible to simultaneously evaluate changes in the three planes of space for both soft and hard tissues using one single model.

The results showed that the soft tissue changes seen on the superimposed models reflected the underlying dento-alveolar changes (Chapter 5). The central part of the upper lip closely followed the anterior alveolar changes (88%) while the soft tissues in the cheek region followed 32% of the underlying transverse alveolar expansion. Interestingly, the amount of transverse alveolar expansion did not seem to correlate with the changes in the upper lip. Since clinically the amount of transverse expansion required is primarily determined by the need to coordinate the upper and lower dental arches, this means that the resulting soft tissue changes in the anterior region are difficult to predict based on the amount of planned transverse expansion.

Predicting the impact of treatment on the patient’s facial outlook with a computer aided maxillofacial planning system has become a vital instrument not only for improved surgical outcome but also for
improved communication with the patients.48 Nowadays, while bone related changes could be reproduced with an acceptable degree of accuracy, prediction of the accompanying soft tissue deformation remains on the other hand challenging. As the current knowledge was extrapolated from 2D records, information from these records tends to be incomplete, especially for treatment modalities producing concomitant changes in the transverse and antero-posterior dimensions. The results of our study provide more detailed 3D information about the effects of such treatment modalities. They could be used to increase the accuracy of the new 3D image based surgery planning systems.48,49

7.3.3 Nasal cavity and airways
Transverse maxillary expansion is associated with enlargement of the nasal cavity and airways50,51 and has been subjectively observed to improve nasal breathing and increase airway patency by increasing alar width and nasal valve size.52 There is, however, no gold standard for measuring the nasal airway. Before the introduction of 3D imaging into routine practice, acoustic rhinometry was the best available tool to provide objective measurements of the nasal airway. This technique was based on the analysis of sound waves reflected from the nasal cavity. By sending a sound pulse into the nose and recording and analyzing the reflected sound, a two-dimensional picture of the nasal cavity was made, from which the volume and the geometry of the nasal cavity could be deduced. With the introduction of CBCT, a direct and accurate evaluation of the changes in soft tissues and airway volumes became feasible.15 Studies on airway diagnostics provided sound scientific data suggesting that CBCT offers a more detailed visualization and quantification of the airway space when compared with conventional radiography and acoustic rhinometry.15,53

In our study we found that both types of expansion resulted in a statistically significant increase in the nose volume and nasal airway volume (Chapter 6). One of the main differences between the two modes of expansion, bone-borne and tooth-borne distraction, was the position of the device on the palate, relative to the center of resistance of the maxilla.22,23 Since bone-borne devices were placed closer to this
centre they would theoretically result in a more parallel expansion of the maxillary segments.\textsuperscript{22,23} Consequently, more widening would be expected in the nasal bony structures leading to a greater increase in the nasal airway volume. Bone-borne distraction did indeed result in slightly more increase in all measured parameters, but the difference was not statistically significant between both groups. To which degree patients would functionally benefit from this increase is not yet clear.\textsuperscript{54} The orthodontic literature has few clinical trials to rely on regarding the influence of nasal expansion on respiration.\textsuperscript{54} While many authors have reported a decrease in nasal resistance after maxillary expansion and decrease in mouth breathing, evidence shows little correlation between subjective symptoms and objective measurement.\textsuperscript{54,55} In other words, despite the fact that SARME has a significant effect on the nasal airway volume, the extent of the clinical benefit of such increase is yet to be fully determined.

### 7.4 Future perspectives

Over the past decade, CBCT has increasingly become an important source of 3D volumetric data in clinical orthodontics.\textsuperscript{46} Surface rendering using special software applications made it also possible to produce truly three-dimensional datasets. Moreover, 3D data from CBCT together with information derived from all other 3D imaging modalities like stereophotogrammetry and digital dental casts can be co-registered into an accurate 3D representation of the patient’s anatomy to create a “virtual patient”. As promising as it may sound to the clinician, the creation of a 3D virtual head or the procedure to fuse these data sets in one 3D model remains time consuming. The process necessitates extensive computation with dedicated software packages and this has limited its use. However, with the fast development pace of 3D imaging technology, the introduction of automated image analysis and simultaneous capture of all required data into a common platform can tremendously simplify the 3D patient documentation and case analysis. This has great potential to facilitate the adaptation of 3D imaging into
daily clinical practice and will soon become an integral part of diagnosis and treatment planning.

Another promising future perspective is the refinement of 3D image based surgery planning systems. The virtual anatomical models could be used to simulate or test treatment options. This process can provide a clearer representation of expected changes following treatment when compared with less sophisticated currently available 2D modeling.

Finally, 3D imaging enables the analysis of the size, shape and volumetric differences in bilateral structures as well as growth changes in 3D. Therefore it offers a more refined and quantifiable diagnosis in all three planes of space that may be significant enough to alter treatment planning decisions. However, despite the abundant amount of information obtained through 3D imaging and image fusion, scientific evidence that its use alters diagnosis and improves treatment outcomes has yet to be established for many of its proposed applications. Future research is needed to elucidate and quantify the added benefits of 3D imaging on treatment procedures, progression and most importantly final outcome.

7.5 References


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Chapter 8

Summary
Chapter 1 is a brief introduction about distraction osteogenesis (DO) and the Eurocran Distraction Study in general and Surgically Assisted Rapid Maxillary expansion (SARME) in particular. The limitations of the application of tooth-borne appliances and the rationale behind the introduction of bone-borne appliances are then presented. SARME has been the topic of numerous investigations, however, the presence of a wide variety of expansion devices and treatment regimes makes it difficult to draw definite conclusions from the literature. Moreover, most studies were performed using dental plaster models despite the fact that SARME does not only influence the position of the teeth but also the alveolar bone, the hard and soft tissues of the mid-face, the nasal cavity and the soft tissues of the nose. Finally, the potentials of three dimensional (3D) imaging modalities like cone beam computed tomography (CBCT) and stereophotogrammetry in enhancing our evaluation of treatment outcomes are explored.

In Chapter 2 the results of a web-based survey, set out to investigate the current practice of DO in Europe, are described. The aim of the survey was to get more insight into the opinion of European surgeons and orthodontists on the use of DO for patients with different diagnoses and treatment protocols. A web-based survey was set up, showing records of four patients with different conditions: hemifacial microsomia, bilateral mandibular deficiency, cleft lip and palate and Crouzon syndrome. Surgeons and orthodontists of 181 Eurocleft centres were asked to fill out a questionnaire for each patient. There was lack of consensus among the respondents about many aspects of DO. Out of six different treatment parameters, an acceptable degree of agreement was only seen in two: a latency period of 3-7 days and a distraction rate of 1 mm per day. Furthermore, there was noticeable disagreement on the ideal age for treatment, surgical technique, distraction device, and retention period. The results showed that there is a wide variety in treatment approaches for craniofacial anomalies in Europe. There is disagreement on essential steps in the distraction procedures.
Chapter 3 describes a study to test the accuracy and reproducibility of CBCT superimposition on the anterior cranial base or the zygomatic arches using voxel based image registration. 16 pairs of 3D CBCT models were constructed from pre- and post- treatment CBCT scans of 16 adult dysgnathic patients. Each pair was registered on the anterior cranial base three times and on the left zygomatic arch twice. Following each superimposition, the mean absolute distances between the 2 models were calculated at 4 regions: anterior cranial base, forehead, left and right zygomatic arches. The results showed that voxel based image registration on both zones could be considered as an accurate and a reproducible method for CBCT superimposition. The left zygomatic arch could be used as a stable structure for the superimposition of smaller field of view CBCT scans where the anterior cranial base is not visible.

In Chapter 4 a prospective cohort study to three-dimensionally assess the long-term effects of tooth-borne and bone-borne SARME is presented. The study comprised 45 consecutive skeletally mature non-syndromic patients with transverse maxillary hypoplasia. In 28 patients, a tooth-borne distractor (Hyrax) was used for expansion, whereas in the remaining 17 a bone-borne distractor (transpalatal distractor, TPD) was used. CBCT scans were performed before treatment and 22 months later, after fixed appliance treatment. 3D models were constructed from CBCT data and superimposed using voxel-based matching. Distance maps between the superimposed models were computed to evaluate the amount of skeletal changes. The distance maps of the superimposed models showed positive distances on the right and left posterior alveolar segments of the maxilla indicating lateral expansion. The anterior maxillary region showed negative distances or posterior displacement and remodelling of the anterior alveolar region. There was no statistically significant difference between TPD and Hyrax for the three alveolar segments ($p$ values ranged from 0.63-0.81). Bone-borne and tooth-borne SARME were found to produce comparable results at the end of fixed appliance treatment regarding skeletal changes.
In Chapter 5 the soft tissue changes in the orofacial region following tooth-borne and bone-borne surgically-assisted rapid maxillary expansion (SARME) were three-dimensionally assessed. The prospective cohort study included 40 skeletally mature patients with transverse maxillary hypoplasia. A tooth-borne distractor (Hyrax) was used for expansion in 25 patients. In the remaining 15, a bone-borne distractor (Transpalatal Distractor, TPD) was used. CBCT scans were acquired before treatment and 22 months later. 3D models were constructed from CBCT data and superimposed using voxel-based matching. Distance maps between the superimposed 3D models were computed to evaluate the degree of skeletal and soft tissue changes in the maxillary region. Distance maps showed negative distances (mean -1.25, SD 1.5 mm) in the middle of the upper lip, indicating posterior repositioning of this area. The cheek region showed positive changes (mean 1.66, SD ± 1.1 mm), reflecting the underlying increase in maxillary width. There was no significant difference between the two groups in all measured distances ($p > 0.05$). Retro-positioning of the upper lip accompanied skeletal remodeling in the anterior alveolar region at a mean ratio of 88%, while the cheek region followed 32% of the alveolar expansion. Soft tissue changes following SARME include posterior repositioning of the upper lip and increased projection of the cheek area. These changes were comparable between bone-borne and tooth-borne appliances.

Chapter 6 describes a study to assess the effects of bone-borne and tooth-borne SARME on the volume of the nose and nasal airway two years post-surgically. Thirty two patients with transverse maxillary hypoplasia were included in this study. In 19 patients, a tooth-borne distractor (Hyrax) was used for expansion, in the remaining 13 a bone-borne distractor (Transpalatal Distractor, TPD) was used. CBCT scans and 3D photographs of the face, acquired prior to treatment and 22 ±7 months later, were used to evaluate the volume of the nose and nasal airway. Nasal volume increased by 1.01 ± 1.6 % in the Hyrax group and by 2.39 ± 2.4 % in the TPD group. Nasal airway volume increased by 9.7 ± 5.6 % in the Hyrax group and 12.9 ± 12.7 % in the TPD group. The changes in nasal volume as well as nasal airway were statistically
significant between T0 and T1 ($p < 0.5$), but were not significant between the groups ($p > 0.5$). Twenty-two months after SARME alar width, volume of the nose, and nasal airway have increased. These changes were comparable between tooth borne and bone borne devices.

*Chapter 7* is a general discussion of the methodological problems encountered during this investigation as well as the clinical significance of the results of the different studies. Finally, the chapter ends with suggestions for future research.
Chapter 9

Samenvatting
Hoofdstuk 1 geeft een korte inleiding over distractie osteogenese (DO) en de ‘Eurocran Distraction Study’ in het algemeen en chirurgisch ondersteunde snelle expansie van de bovenkaak (surgical assisted rapid maxillary expansion = SARME) in het bijzonder. De beperkingen van de toepassing van tandgedragen apparaten en de rationele achter de invoering van botgedragen apparaten worden vervolgens gepresenteerd. SARME is het onderwerp van talrijke onderzoeken, echter de aanwezigheid van een grote verscheidenheid aan apparaten en behandelingen voor expansie van de bovenkaak maakt het moeilijk om definitieve conclusies te trekken uit de literatuur. Bovendien werden de meeste studies uitgevoerd met behulp van gipsmodellen van het gebit, ondanks het feit dat SARME niet alleen de positie van de gebitselementen beïnvloedt, maar ook het alveolaire bot, de benige en weke delen van het middelste deel van het gelaat en de neus, alsmede de grootte van de neusholte. Ten slotte worden driedimensionale (3D) beeldvormende technieken zoals cone beam CT (CBCT) en stereofotogrammetrie onderzocht op hun potentie om tot een betere evaluatie van behandelresultaten te komen.

In hoofdstuk 2 worden de resultaten van een internetenquête, opgezet om de huidige praktijk van DO in Europa te onderzoeken, beschreven. Het doel van het onderzoek was om inzicht te krijgen in verschillende behandelprotocolen van Europese chirurgen en orthodontisten voor de toepassing van DO bij patiënten met verschillende diagnoses. Een internetenquête werd opgezet, waarin de gegevens getoond werden van vier patiënten met verschillende aandoeningen: hemifaciale microsomie, mandibulaire retrognathie, schisis en Crouzon syndroom. Maxillofaciaal chirurgen en orthodontisten van 181 Eurocleft centra werden gevraagd een vragenlijst in te vullen voor iedere patiënt. Over veel aspecten van DO bestond gebrek aan consensus onder de respondenten. Voor slechts twee van de zes verschillende behandelingparameters werd een aanvaarbare mate van overeenkomst gezien: een latentieperiode van 3-7 dagen en een mate van distractie van 1 mm per dag. Verder was er een duidelijk verschil van mening over de ideale leeftijd voor de behandeling, de chirurgische
techniek, het distractieapparaat en de retentieperiode na distractie. De resultaten toonden aan dat er een grote variatie bestaat in behandelprotocollen voor craniofaciale afwijkingen in Europa. Er bestaat verschil van mening over essentiële stappen in de distractieprocedure.

In hoofdstuk 3 wordt de nauwkeurigheid en de reproduceerbaarheid besproken van het superponeren van CBCTs op de voorste schedelbasis en de jukbeenderen door middel van voxel based registratie. Uit de CBCT scans vóór en na behandeling van 16 volwassen patiënten met een dysgnathie werden 16 paren 3D-CBCT modellen geconstrueerd. Elk paar werd driemaal op de voorste schedelbasis en tweemaal op de linker jukbeenboog gesuperponeerd. Na elke superpositie werden de gemiddelde absolute afstanden tussen de 2 modellen berekend op 4 regio's: voorste schedelbasis, voorhoofd, linker en rechter jukbeenderen. De resultaten laten zien dat voxel based registratie op beide anatomische gebieden kan worden beschouwd als een nauwkeurige en reproduceerbare methode voor superpositie van CBCTs. De linker jukbeenboog kan gebruikt worden als een stabiele structuur voor de superpositie van CBCT scans waarin de voorste schedelbasis niet zichtbaar is.

In hoofdstuk 4 wordt een prospectieve cohort studie gepresenteerd naar de drie-dimensionale effecten van SARME op de lange termijn, waarbij tandgedragen of botgedragen expansieapparatuur werd toegepast. De studie omvatte 45 opeenvolgende volwassen niet-syndromale patiënten met een transversale maxillaire hypoplasie. Bij 28 patiënten werd een tandgedragen distractor (Hyrax) gebruikt voor expansie terwijl bij de overige 17 patiënten een botgedragen distractor (transpalatinale distractor, TPD) werd gebruikt. CBCT scans werden gemaakt voorafgaand aan en na afloop van (22 maanden later) orthodontische behandeling met vaste apparatuur. Uit de CBCT scans werden 3D-modellen geconstrueerd en deze werden gesuperponeerd door middel van voxel based registratie. Als maat voor de veranderingen ten gevolge van de behandeling werd de afstand tussen de gesuperponeerde 3D-modellen berekend. De gesuperponeerde
modellen lieten positieve veranderingen zien voor de zijdelingse delen van de bovenkaak wat duidt op laterale expansie. Het voorste deel van de maxilla toonde negatieve afstanden oftewel een achterwaartse verplaatsing en remodellering van de voorste alveolaire regio. Er was geen statistisch significant verschil tussen TPD en de Hyrax voor de drie alveolaire segmenten (p-waarden varieerden van 0.63 tot 0.81). Botgedragen en tandgedragen SARME bleken in vergelijkbare skeletale veranderingen te resulteren na afloop van orthodontische behandeling met vaste apparatuur.

In hoofdstuk 5 wordt het onderzoek beschreven waarin veranderingen in de weke delen van de orofaciale regio na tandgedragen en botgedragen SARME drie-dimensionaal werden beoordeeld. De prospectieve cohort studie omvatte 40 uitgegroeide patiënten met een transversale maxillaire hypoplasie. Bij 25 patiënten werd een tandgedragen distractor (Hyrax) gebruikt voor verbreding van de bovenkaak. Bij de overige 15 patiënten werd een botgedragen distractor (transpalatinale distractor, TPD) gebruikt. CBCT scans werden voor de behandeling gemaakt en 22 maanden later. Van deze CBCT scans werden 3D-modellen gereconstrueerd en gesuperponeerd met voxel gebaseerde beeld registratie. Afstanden tussen de gesuperponeerde 3D-modellen werden berekend om de skeletale en weke delen veranderingen in de regio van de bovenkaak te evalueren. Negatieve afstanden (gemiddelde -1.25 mm; SD 1.5 mm) werden gevonden voor het middendeel van de bovenlip, wat duidt op achterwaartse verplaatsing van dit gebied. De regio van de wang toonde positieve veranderingen (gemiddelde 1.66 mm, SD ± 1.1 mm), als gevolg van de toename van de onderliggende maxillaire breedte. Er werden geen significant verschillen gevonden tussen de toegepaste distractoren (p>0.05). De achterwaartse verplaatsing van de bovenlip volgt de skeletale remodellering in het voorste alveolaire gebied met een gemiddelde ratio van 88%, terwijl de regio van de wang 32% van de alveolaire expansie volgt. Wij concludeerden dat veranderingen van weke delen na SARME bestaan uit achterwaartse verplaatsing van de bovenlip en een toename
Hoofdstuk 6 beschrijft een studie naar de effecten van botgedragen en tandgedragen SARME op het volume van de neus en de nasale luchtwegen twee jaar na de operatie. Tweeëndertig patiënten met een transversale maxillaire hypoplasie werden in deze studie geïncludeerd. Bij 19 patiënten werd een tandgedragen distractor (Hyrax) gebruikt voor expansie, in de overige 13 patiënten werd een botgedragen distractor (transpalatinale distractor, TPD) gebruikt. CBCT scans en 3D-foto's van het gezicht, gemaakt voorafgaand aan de behandeling en 22 ± 7 maanden later, werden gebruikt om het volume van de neus en de nasale luchtwegen te evalueren. Het volume van de neus nam met 1,01 ± 1.6% in de Hyrax groep toe en met 2.39 ± 2.4% in de TPD-groep. Het volume van de nasale luchtwegen steeg met 9.7 ± 5.6% in de Hyrax groep en met 12.9 ± 12.7% in de TPD-groep. De veranderingen in het volume van de neus en nasale luchtwegen waren statistisch significant tussen T0 en T1 (p<0,5), maar waren niet significant tussen beide groepen met verschillende distractoren (p>0.5). Tweeëntwintig maanden na SARME zijn het volume van de neus en de nasale luchtwegen toegenomen. Deze veranderingen waren vergelijkbaar tussen tandgedragen en botgedragen distractoren.

Hoofdstuk 7 is een algemene bespreking van de methodologische problemen in dit onderzoek en de klinische betekenis van de resultaten van de verschillende deelonderzoeken. Het hoofdstuk eindigt met suggesties voor toekomstig onderzoek.
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Curriculum Vitae

Rania Nada was born in Cairo, Egypt on March 23, 1976. In 1995, she completed her pre-university secondary education at Notre Dame de la Délivrande in Heliopolis, Cairo. In 1999 she obtained her Bachelor Degree in Oral and Dental Medicine with honors ranking 2\textsuperscript{nd} on her class from the Faculty of Oral and Dental Medicine, Cairo University, Egypt. She then spent one year in training as an intern at the different departments of the University hospital. In January 2001 she took a small detour from her dental career and got a scholarship from the Egyptian Ministry of Telecommunications in collaboration with IBM Egypt to study Information Technology for 8 months specializing in e-learning, Web-designing and development. At the end of 2001, she started her residency at the Department of Orthodontics, Cairo University. During her residency, in 2002 she spent one month as an exchange student at the Department of Orthodontics, Case Western Reserve University, Cleveland, Ohio, USA. In 2005, she successfully passed the examination for the Diploma of Membership in Orthodontics (MOrth) from the Royal of College of Edinburgh and a year later in 2006 she successfully defended her Master thesis and obtained a Master Degree in Orthodontics and Pediatric dentistry from Cairo University, Egypt. Shortly afterwards, she started her PhD at the department of Orthodontics and Craniofacial Biology, Radboud University, Nijmegen Medical Centre and joined the 3D Facial Imaging Group Nijmegen-Bruges. In 2010 she won the prize for the best research presentation during the 3\textsuperscript{rd} International Congress on 3D Diagnosis and Virtual Treatment Planning. Rania still keeps her position as an assistant lecturer at the department of Orthodontics, Cairo University, Egypt.
Publications


6. Nada RM, van Loon B, Schols JG, Maal TJ, Bergé SJ, Mostafa YA, Kuijpers-Jagtman AM. Volumetric changes of the nose and nasal airway two years after tooth borne and bone borne surgically assisted rapid maxillary expansion. (submitted)

