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Original Article

Dentoskeletal effects of mini-screw assisted, non-surgical palatal expansion in adults using a modified force-controlled polycyclic protocol: a single-centre retrospective study

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Abstract

Objectives: This study assessed the dental and skeletal effects of pure bone-borne, non-surgical maxillary expansion, using a modified force-controlled polycyclic protocol.

Methods: Records of 17 adult patients, mean age 24.1 years; range 18–39 years, who had undergone maxillary expansion using a bone-borne Quad-expander (with 4 mini-screws), were analysed. In all patients, 0.17 mm/day of expansion was completed for 1 week, followed by a cyclic protocol of expansion of forward and backward turns until the force needed to turn the expander was below 400 cN, assessed weekly. After this, expansion continued at a rate of 0.17 mm/day until the desired amount of expansion was achieved. Cone beam computer tomography scans were taken pre- and post-expansion.

Results: The mid-palatal suture was successfully opened in 100% of patients included in this study. Axially, the amount of skeletal opening at the posterior nasal spine was 61% of the anterior nasal spine. Expansion was pyramidal in the coronal plane. Significant increases at the dental and skeletal levels were achieved, with changes at the skeletal level reaching 73%. The alveolar bone angle increased more than the angular changes at the molars and premolars.

Limitations: This is a retrospective study with short-term results.

Conclusion: The Quad-expander, with a force-controlled polycyclic expansion protocol, effectively produced a significant increase in maxillary width in skeletally mature subjects in the short term.

Keywords: Expansion; Skeletal Anchorage; Adult expansion; Bone borne expansion

Introduction

Transverse maxillary deficiency is highly prevalent amongst the orthodontic population, and rapid maxillary expansion (RME) is commonly used to expand and correct transverse width discrepancies of the maxilla. Conventional orthopaedic maxillary expansion has traditionally been reserved for paediatric and adolescent populations, aiming to be performed prior to the fusion of the mid-palatal suture (MPS) [1]. It has been deemed unsuitable in adults due to potential complications in those who exhibit signs of MPS interdigitation [2]. Instead, skeletally mature individuals are subject to a more invasive surgically assisted rapid maxillary expansion (SARME). However, SARME has it is own complications and drawbacks, including the risks associated with a general anaesthetic, as well as the complications associated with surgery [3]. Furthermore, a recent systematic review noted that the amount of maxillary expansion that is achieved with SARME is limited and instead recommended other non-surgical forms of expansion [4]. In an attempt to optimize skeletal outcomes in older adolescent and adult patients whilst avoiding the invasive nature of SARME, alternative methods of non-surgical expansion have been explored in the last decade.

A number of hybrid skeletally anchored expanders have been introduced with the aim of transmitting expansion forces directly to the palatal bone to maximize skeletal outcomes and minimize dental side effects in adolescent and adult patients [5, 6]. These appliances are both tooth and bone borne as they utilize mini-screws as well as attachment to the maxillary first molars. More recently, however, pure bone-borne appliances that are skeletally anchored via four mini-screws, without any attachments to the teeth, have been gaining popularity for use in adults.

Winsauer *et al.* proposed that when MARPE is used with a continuous opening expansion protocol in adult patients, commonly two activations per day, the hardware can become overloaded [7]. This can lead to breakage or loosening of the appliance/mini-screws as well as undesirable effects to adjacent anatomical structures [3, 8]. Furthermore, the increased interdigitation of the MPS and reduced elasticity of bones in adults may lead to micro-fractures of the bone around the cranial base, resulting in injury to nervous and vascular structures [7, 9]. Winsauer thus developed the Micro-4 expander with increased rigidity for use with a two-staged protocol for mini-screw assisted palatal expansion in adults called the force-controlled polycyclic protocol (FCPC) [7]. The aim of this protocol is to weaken the circum-maxillary sutures and enable a more physiological expansion of the MPS. A variation of Winsauer's protocol [7] was used in this study to determine if successful results can also be achieved with this modified activation protocol, which requires weekly force measurements, in patients that had forces exceeding 400 cN.

There are only a few studies in the literature examining the effects of pure bone-borne expansion in adult populations, with only a single study reporting on the success of force-controlled slow maxillary expansion and no studies investigating the dental and skeletal effect of FCPC on the craniofacial complex in non-growing populations [7, 10]. Thus, the purpose of the current study is to assess outcomes following pure bone-borne palatal expansion, using a force-controlled slow rate of maxillary expansion, on skeletal and dental structures of skeletally mature adults where growth of the MPS and circum-maxillary sutures have ceased.

Subjects and methods

Study design

This retrospective study was approved by the Ethics Review Committee of the Sydney Local Health District RPAH Zone (X21-0493 & 2021/ETH12483). Records of all adult subjects, treated between 2019 and 2022, who had undergone expansion treatment using a Quad-expander (Four mini-screws attached to an expansion screw) with a modification of the Winsauer FCPC protocol and were screened from a single private practice in Sydney, Australia 17 patients (9 females and 8 males) who fulfilled the inclusion criteria and who had CBCT imaging available and landmarks visible at both timepoints were included in the study. All patients were treated by the same practising Orthodontist (NET). Cone beam computer tomography (CBCT) imaging was taken before and within 1 month after the expansion was completed. The CBCTs at those two timepoints were not taken solely for research purposes. They are routinely taken at the treating orthodontist's practice, at T1 to aid in diagnosis and treatment planning, specifically to detect the ideal location and length of the palatal mini-screws, and at T2 for those that are treated with SureSmile™ (OraMetrix, Richardson, Tex) digital planning.

Inclusion criteria

Patients who were treated between 2019 and 2022 were eligible for inclusion if: (i) they were older than 18 years of age; (ii) had a transverse skeletal maxillary deficiency (>4 mm) treated with a pure bone-borne expansion appliance; (iii) had pre-expansion and post-expansion CBCT scans, with the field of view including the orbit and all measurement structures clearly visible.

Patients who had a history of craniofacial defects or syndromes, or prior treatment were excluded. Patients were also excluded if there was missing CBCT data or missing landmarks (i.e. orbit).

Technique

Under local anaesthesia, four orthodontic palatal mini-screws (Benefit PSM Medical Solutions, Gunningen, Germany) were inserted with predrilling, two between the first and second premolar region (between the palatal midline and palatal cusp of the first premolar) in the anterior palate whilst two posterior mini-screws were inserted in the alveolar process between the second premolar and first molar roots at approximately 8–9 mm from the gingival margin. Cone beam computed tomography (CBCT) was used to plan the length of the mini-screws in each patient aiming for bi-cortical anchorage anteriorly. Mini-screws were either 9, 11, or 13 mm in length, with a diameter of 2 mm. Appliance fabrication was carried out as per Graf *et al.* [11]. After placement of the mini-screws, an intraoral scanner (Trios Pod Version, 3Shape, Copenhagen, Denmark) was used to create a stereolithography (STL) file of the maxillary arch and was sent to the technical laboratory for design and appliance construction. The framework was digitally designed using 3Shape Appliance Designer software (3Shape, Copenhagen, Denmark), to ensure the framework conformed well to the palatal contours and provided sufficient rigidity for expansion forces. The appliance design was then exported to a laser melting machine (Concept Laser, General Electric Company, CT, USA) and printed using the alloy Remanium (Dentaurum, Ispringen, Germany). Once printed, a PowerScrew expansion mechanism (Tiger Dental, Bregenz, Austria) was laser-welded to the bedding prepared in the framework. The finished appliance was inserted into the patients' mouth and secured to the mini-screws with fixation screws (Benefit PSM Medical Solutions, Gunningen, Germany). The final expander design can be seen in Fig. 1.

The activation protocol followed was a variation of the Winsauer force-controlled polycyclic (FCPC) activation protocol of expansion [7]. The expansion screw was turned once daily (0.17 mm) for 1 week with a wrench turning the hex nut of the expansion screw and observed for a diastema. After 1 week of expansion, the subject visited the orthodontist who measured the amount of force required to turn the expansion screw using a spring scale (Push–Pull Spring Scale 10N, Arbour Scientific, Ann Arbor, USA). The ideal force required to turn the screw was selected to be between 150 and 400 cN.

- If the spring scale measured under 400 cN, the subject was instructed to turn the expansion screw once daily (0.175 mm) for another week and the force was reassessed again. If it stayed under 400 cN the patients were asked to continue until the desired expansion was achieved.
- If the force exceeded 400 cN after the first or the second week, the expansion screw was turned 1 mm or until the spring scale read under 400 cN. Then to weaken the circum-maxillary sutures, patients were instructed to apply the following protocol: turn the expansion screw forward twice in the morning (expansion of 0.34 mm), wait for 10 min, then close the screw back twice

(constriction of 0.34 mm) and leave for the rest of the day. In the evening, patients were instructed to turn the screw once forward (expansion of 0.17 mm). Patients were to follow this daily FCPC protocol for 1 week. After 1 week, the subjects visited the orthodontic practice again to assess the force of expansion with the spring scale. This protocol was followed until the weekly spring scale measurement read under 400 cN, indicating no resistance to expansion, and at this point, patients were instructed to turn the expansion screw once daily until adequate expansion was achieved as assessed by the treating orthodontist. All patients exhibited a visible diastema at their review appointments indicating skeletal expansion was achieved.

Complications were gathered from the patient records including pain/discomfort, periodontal changes, and hardware-related side effects (failure of the mini-implant and fracture of the expansion device).

Radiographic evaluation

CBCT images were taken using the iCAT FLX CBCT (Imaging Sciences International, USA) imaging system at 120 kVp, 5 mA, 23 × 17 cm, 0.3 mm voxel size, scan time of 17.8 s with 7.4 s of exposure with patients in a standing position and taken pre-expansion as well as within 1 month of completing expansion. The image volume and reorientation process and CBCT analysis were adopted from the methods by Ngan *et al.* and Kartalian *et al.* [12, 13]. The DICOM-formatted images were rendered into volumetric images, and cross-sectional slices were made with InVivo dental software (Anatomage, San Clara, CA). To set an identical reference plane in the T0 and T1 images, the CBCT images were initially orientated parallel to the mid-palatal suture (axial section), parallel to the palatal plane (ANS-PNS) (sagittal section), and tangent to the nasal floor at its most inferior level (coronal section). Reorientation of the scans was then performed in all three dimensions (axial, coronal, and sagittal) through the upper right first molar (tooth 16) locating the middle of the pulp chamber. A similar method was undertaken for the upper right first premolar (tooth 14), locating the middle of the pulp chamber in all three dimensions. Transverse and angular measurements were then recorded for each T0 and T1 scan and the changes from T0 to T1 were then determined. Identification of the dentoskeletal landmarks and subsequent measurements were manually performed by one investigator for both T0 and T1 scans.

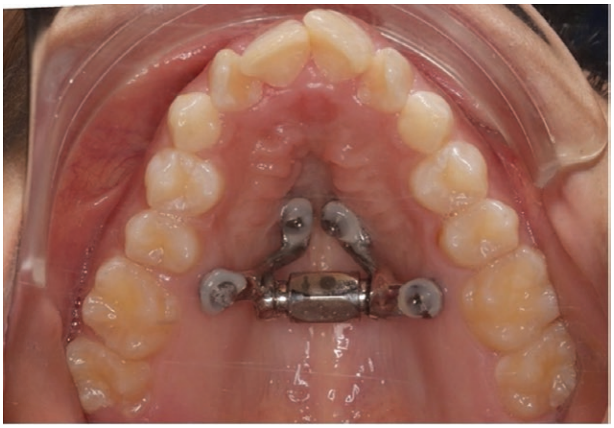

Figure 1. 3D printed bone-borne maxillary expander (Quad-expander).

Measurements in the coronal plane

Transverse measurements:

- External cranial width measurements (Fig. 4)
- External and internal maxillary width measurements (Fig. 5)

Angular measurements (Fig. 6 and 7)

- Left and right maxillary first molars and premolars

Measurements in the axial plane

Transverse measurements were recorded in the T1 scan at the lower border of the internal hard palate (HP) (Fig. 8).

Intra-oral measurements

Intra-oral scans were taken pre and post expansion using the Trios scanner. STL files of the maxillary arch were used to take linear measurements and determine the amount of expansion achieved between the anterior mini-screws as well as the post mini-screws and amount of opening of the expansion screw.

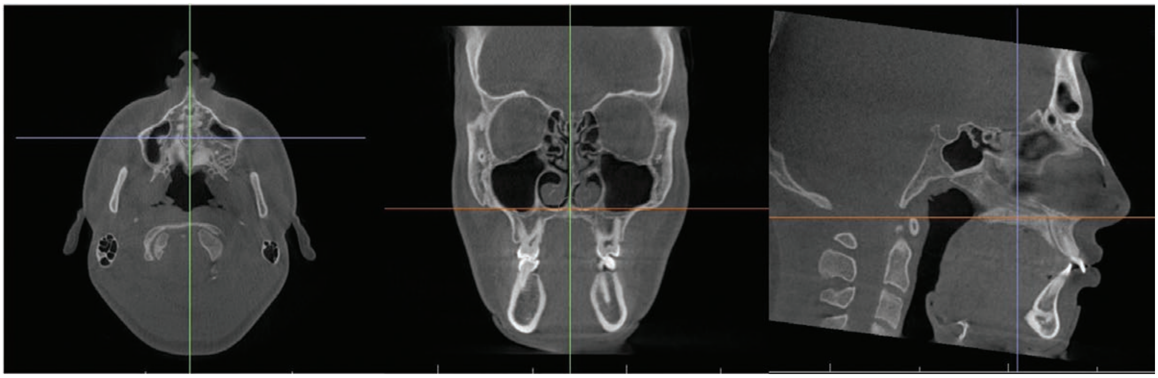

Figure 2. Orientation of CBCT images orientated parallel to the midpalatal suture (axial section), parallel to the palatal plane (ANS–PNS) (sagittal section), and tangent to the nasal floor and its most inferior level (coronal section).

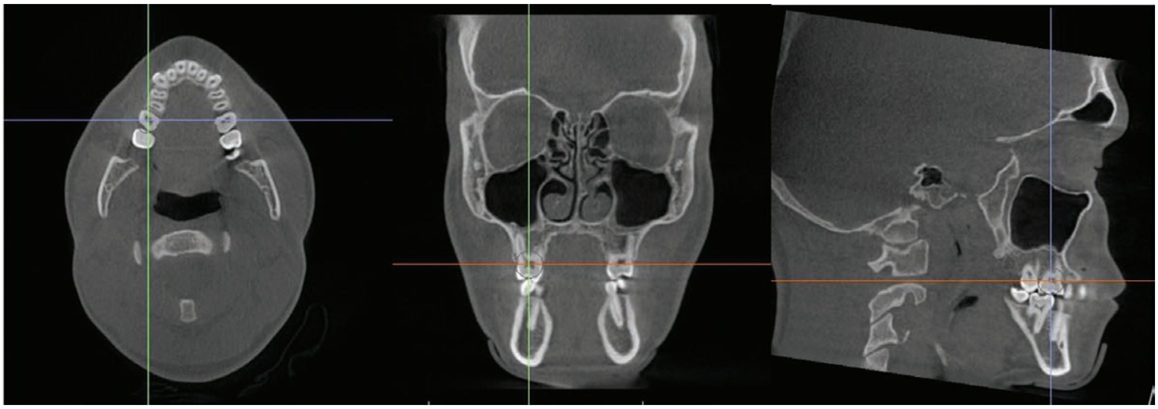

Figure 3. Reorientation of scans in all three dimensions (axial, coronal, and sagittal) through the upper right first molar (tooth 16) locating the middle of the pulp chamber.

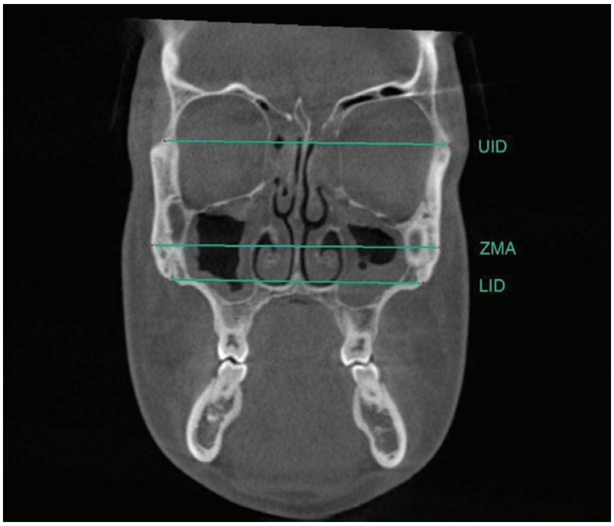

Figure 4. External cranial measurements in the coronal view: ZMA, width between the right and left zygomatic arches at its widest point at the most inferior level of the orbits; UID, distance from the most external point of the right frontozygomatic suture to the most external point of the left frontozygomatic suture; LID, distance from the most external point of the right zygomaticomaxillary suture to the most external point of the left zygomaticomaxillary suture.

Statistical analysis

A sample size analysis resulted in a minimum sample size of 17 subjects based on an alpha of 0.05, a power of 95% (G Power, version 3.1.9.7., Dusseldorf, Germany) based on Park *et al.* [14]. All measurements were performed by the same investigator (PP). A random selection of 40% of the measurements was repeated after 4 weeks and intra-observer reliability was assessed using the intraclass correlation coefficient (ICC). All continuous variables are presented as mean ± standard deviation. Independent sample *t* test was used for the comparison of the means of all variables and gender. Paired samples *t*-test was used to analyse differences between pre and post-treatment measurements. Shapiro–Wilk test was used to check for normality of the variables. Pearson correlation coefficient (R) was calculated for the correlation between age and all variables. Statistical significance level $P < 0.001$ was chosen. IBM SPSS Statistics for Windows (Version 28.0). Armonk, NY: IBM Corp was used to analyse the data.

Results

The mean age of patients was 24.1 years (range 18–39). Ten subjects were excluded due to missing data or difficulty in reading the CBCT image although these excluded patients also exhibited evidence of suture opening on CBCT images.

All patients achieved the desired expansion, resulting in a success rate of 100%, with an average amount of activation of the expansion screw of 7.7 mm (range 5.73–10.54) over a mean period of 115 days.

The differences between the repeated measurements were analysed by computing ICCs. The intraclass correlation coefficient was at least 0.849 for the angular measurements and 0.809 for the transverse measurements, indicating that most measurements had good or excellent reliability. Only one measurement exhibited moderate reliability, BAC at first maxillary molar, with an ICC of 0.745.

Linear measurements

All transverse measurements showed significant changes ($P < 0.001$) except for the upper inter-zygomatic distance (UID). Nasal width increased by a mean 3.50 mm ± 1.39 ($P < 0.001$). Maxillary width at the level of the HP increased 2.56 mm ± 1.80 ($P < 0.001$) (Table 1, Supplementary Fig. 6).

At the dental level, the mean increase was 4.97 mm ± 1.73 ($P < 0.001$) at the buccal alveolar crest of the maxillary first molars (BAC6) and 5.46 mm ± 1.87 ($P < 0.001$) in the dental arch width measured at the level of the buccal cusp tips of the maxillary first molars (ICW6), whilst at the first premolars there was an increase of 5.57 mm ± 1.76 ($P < 0.001$) at the buccal cusp tips (ICW4).

Further cranially, changes at the upper inter-zygomatic distance (UID) were not significant with a mean change of −0.24 mm ± 2.83 ($P = 0.734$) whilst changes at the lower inter-zygomatic distance (LID) were significant with a mean increase of 2.41 mm ± 1.66 ($P < 0.001$). Changes between the left and right zygomatic arches (ZMA) were also significant with a mean change of 2.54 mm ± 1.59 ($P < 0.001$).

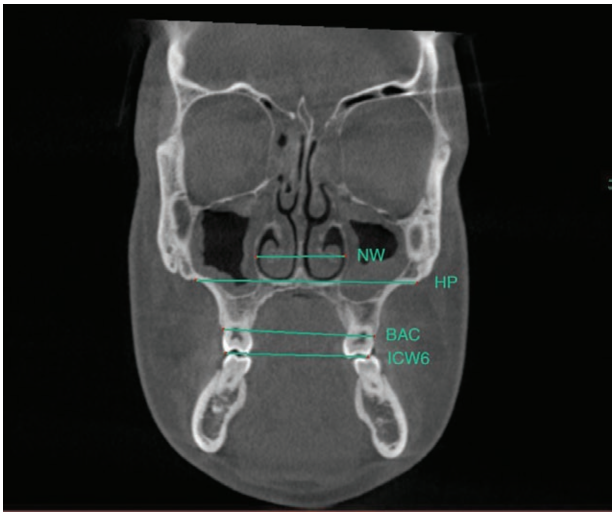

Figure 5. External and internal maxillary measurements in the coronal view: NW, width of the nasal cavity at its widest dimension; HP, maxillary width parallel to the lower border of the hard palate and tangent to the hard palate at its most superior level; BAC, maxillary width between the buccal alveolar crests of the maxillary first molars; ICW6, dental arch width measured at the level of the buccal cusp tips of the maxillary first molars.

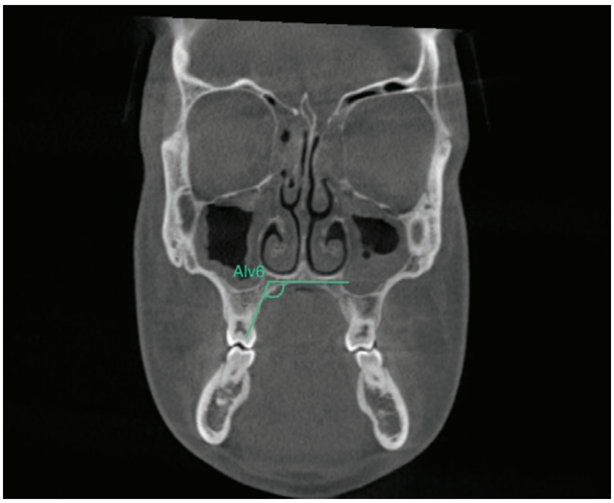

Figure 6. Angular measurements in the coronal view: Alv6, angle between the palatal alveolar crest of the maxillary first molar and the internal hard palate.

Angular measurements

The mean between left and right molar and premolar measurements was calculated. The angular change of the alveolar bone at the upper first molar (Alv6) and premolar (Alv4) was 1.26°and 0.23° of buccal movement, respectively (Tables 1 and 2, Supplementary Fig. 7). Inclination of the upper first molar (Incl6) and premolar (Incl4) exhibited mild increases with a mean change of 0.44° and 0.02°, respectively, which is less than the alveolar bone tipping, which were not significant.

Transverse measurements in the axial plane

Initial values of ANS and PNS at T0 were 0 mm as they were a singular landmark before the commencement of expansion (Table 3, Supplementary Fig. 8). Expansion resulted in an increase in transverse dimension at the ANS of a mean 5.34 mm ± 1.54 mm and PNS 3.27 mm ± 0.92 mm.

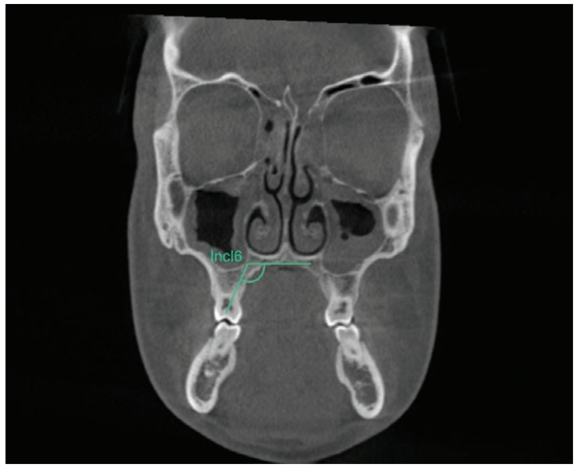

Figure 7. Angular measurements in the coronal view: Incl6, angle between the palatal root of the maxillary first molar and the internal hard palate.

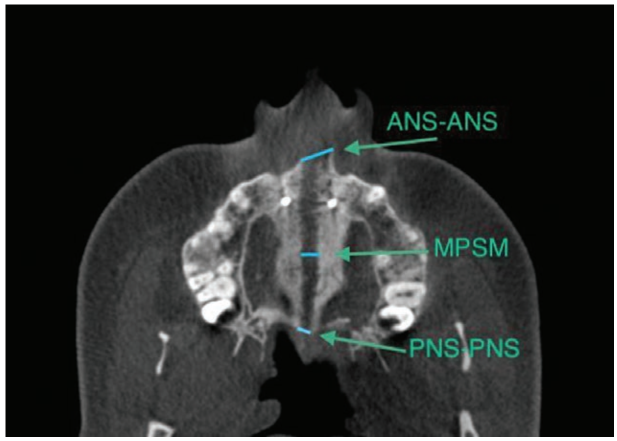

Figure 8. Transverse measurements at the lower border of the internal hard palate: ANS–ANS, distance between the right anterior nasal spine and the left anterior nasal spine; MPSM, width of the mid-palatal suture at the level of the first molars; PNS–PNS, distance between the right posterior nasal spine and the left posterior nasal spine.

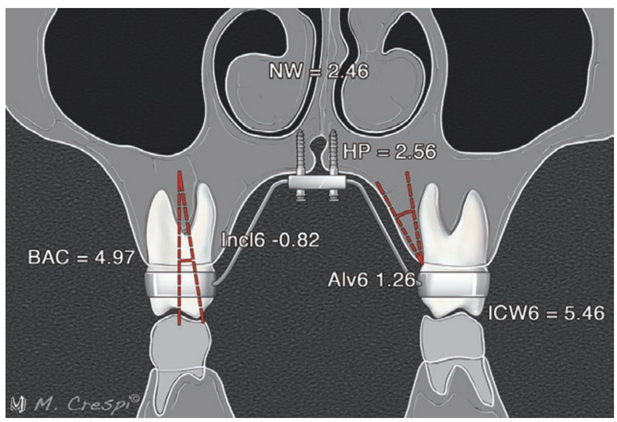

Figure 9. Mean width (mm) and angular changes (o) from T0 to T1.

To determine the pattern of expansion in the axial plane, the amount of expansion at the PNS was compared to the amount at the ANS. PNS expansion was 61% of the amount at the ANS indicating a V-shaped pattern of expansion. When compared to the total expansion experienced in the appliance

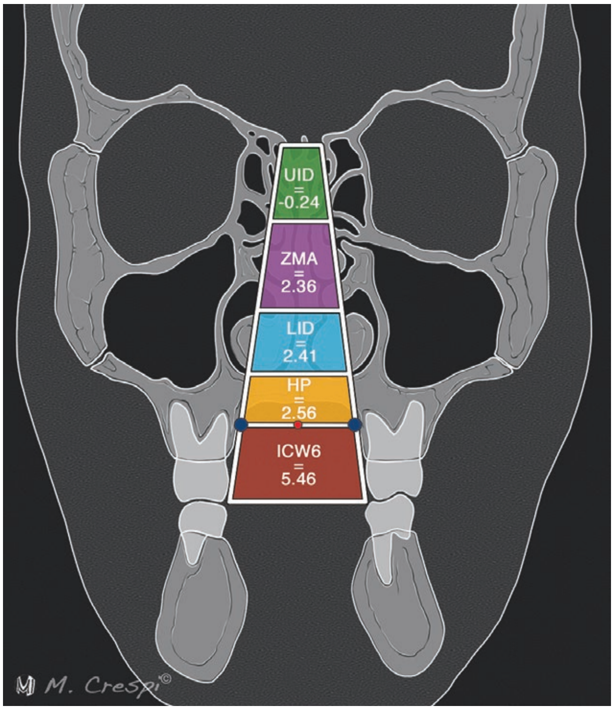

Figure 10. Mean width changes from T0 to T1 (mm) in the coronal plane.

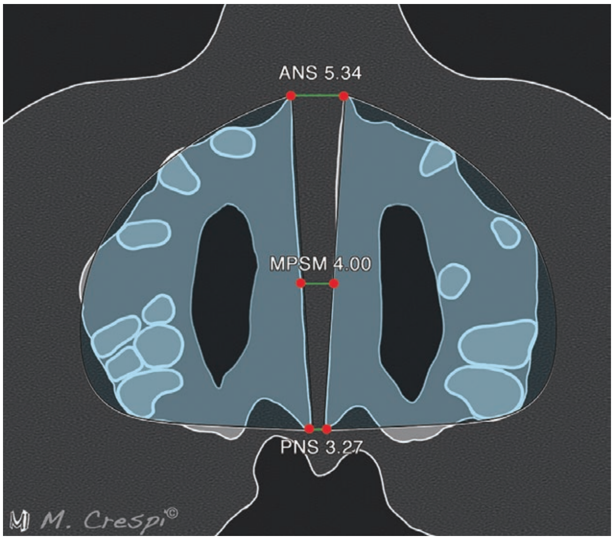

Figure 11. Mean width changes from T0 to T1 (mm) in the axial plane.

(7.7 mm), the ANS expanded 69.4% of the total expansion, whilst the PNS expanded 42.5%.

To determine the level of skeletal expansion experienced, the mean expansion at the MPS at the level of the molar (MPSM) was compared to the total expansion experienced at the molar (ICW6), showing 73%.

The mean amount of expansion exhibited between the anterior mini-screws and posterior mini-screws were 5.93 mm and 5.31 mm, respectively, with the posterior tad experiencing 89.5% of the amount of expansion experienced at the anterior mini-screw. When comparing to the total expansion of the appliance, the anterior mini-screw expanded 77% of the total expansion and the posterior mini-screw 69%, illustrating an almost parallel expansion at the level of the mini-screws.

A linear regression analysis was performed and found no correlation between age and gender and the amount of expansion in our sample. Complications occurred in three subjects (17.65%) with two fractures of the hardware and one mini-screw failure, requiring replacement during treatment. Four patients (23.5%) reported mild pain or feeling pressure during the expansion stage. Gingival recession and bone levels were not assessed in this study, however, should be explored in future studies.

Discussion

This study is the first to investigate the dental and skeletal changes experienced after expansion with a purely bone-borne expander using a modified force-controlled protocol on skeletally mature subjects. The MPS was successfully opened and the desired expansion was achieved in all patients in the present study, suggesting that non-surgical expansion in skeletally mature patients is possible. The 100% success rate is similar or higher than those reported by similar studies, as well as those utilizing the Maxillary Skeletal Expansion (MSE) and MARPE appliances [3, 7, 12, 15].

The mean age of patients in this study was 24.14 years, which is lower than Winsauer *et al.*'s (29.1 years) study, however, higher than other studies (13.8–19.2 years) using other bone-borne devices [7, 10, 16–20]. Winsauer *et al.* noted that the higher success rate experienced with the Micro-4 expander in older patients may be due to the increased rigidity of the appliance, the anterior location of the mini-screws in an area of the palate with greater bone height, and due to the novel 2-stage protocol [7]. Nevertheless, our results show a higher success rate than Winsauer *et al.*, which may be directly related to the younger age of our patients (18–58 years [7] versus 18–39 years, respectively).

The criticism of other bone-borne appliances that apply a rapid protocol of expansion, of one to two turns of the expansion screw per day, is that in adults with nonelastic bone, higher stresses are induced on the cranial base that can cause micro-fractures of the bone and may lead to possible injuries on neural and vascular structures [9]. The controlled force expansion protocol employed in this study, however, involves alternate opening and closing of the expansion screw. These alternating tensile and compressive forces have been demonstrated to upregulate sutural cell proliferation and stimulate sutural growth in the nasomaxillary and nasofrontal sutures [21]. It is believed that the alternating protocol may gradually weaken the circum-maxillary sutures and result in their successful opening whilst reducing the risk of micro-fractures of the interdigitated osseous bone surfaces.

The mean amount of screw activation achieved in this study was 7.74 mm, however, the extent of activation differed between patients depending on the amount of expansion required. The subjects in this study exhibited increases in the width of the maxilla (2.56 mm; SD 1.8) that were comparable to those exhibited in growing children with traditional RME appliances and patients treated with MSE [10, 13, 22]. Lin *et al.* utilized a tissue-bone-borne C-expander with four palatal mini-screw and an acrylic resin cover in patients with a mean age of 18.1 years. After activating the central screw 7 mm at placement and another one-quarter turn per day, patients in their study exhibited increases at the hard palate level of 1.99 mm (SD 1.18), which is less than that achieved in our patients. The skeletal contribution to the total expansion in our

Table 1. Distance and angular measurements at T0 and T1, and differences (T1–T0).

	T0		T1		T1–T0					
	Mean	SD	Mean	SD	Mean	SD	SE	95% CI		*P*
								Lower	Upper	
Distance measurements (mm)										
ZMA width	102.61	5.53	104.97	5.90	2.36	1.85	0.46	1.37	3.35	<0.001
UID	101.41	4.75	101.17	3.04	–0.24	2.83	0.69	–1.69	1.22	0.73
LID	89.03	5.07	91.45	4.36	2.41	1.66	0.40	1.56	3.27	<0.001
Nasal width	29.99	2.17	33.49	2.39	3.50	1.39	0.34	2.79	4.21	< 0.001
Hard palate width	64.91	4.52	67.47	4.57	2.56	1.80	0.44	1.63	3.48	<0.001
BAC at 6	53.03	3.95	58.00	4.27	4.97	1.73	0.42	4.08	5.87	<0.001
ICW6	51.25	4.88	56.70	5.43	5.46	1.87	0.45	4.50	6.42	<0.001
ICW4	39.68	4.04	45.25	3.73	5.57	1.76	0.43	4.66	6.48	<0.001
Angular measurements										
Alv6 right	101.76	6.84	103.35	7.61	1.59	4.82	1.17	–0.89	4.07	0.19
Alv6 left	105.69	12.12	106.61	10.24	0.92	3.98	0.96	–1.13	2.96	0.36
Alv4 right	109.21	10.60	108.21	9.50	–1.00	5.51	1.34	–3.83	1.83	0.47
Alv4 left	105.92	9.88	107.38	8.15	1.45	6.24	1.51	–1.76	4.66	0.35
Incl6 right	108.16	6.97	108.29	5.23	0.12	5.40	1.31	–2.66	2.90	0.93
Incl6 left	105.84	11.01	106.60	9.88	0.77	2.60	0.63	–0.57	2.10	0.24
Incl4 right	98.51	3.60	98.67	5.97	0.17	5.79	1.41	–2.81	3.14	0.91
Incl4 left	89.97	8.19	89.85	8.26	–0.12	3.59	0.87	–1.97	1.73	0.89

Table 2. Angular change differences between alveolus and teeth at the first molars (6s) and first premolars (4s) for right and left sides (in degrees).

	Mean	SD	SE	95% CI		*P*
				Lower	Upper	
Angular change difference (6s)	0.81	3.26	0.79033	–0.867	2.484	0.32
Angular change difference (4s)	0.22	4.24	1.02902	–1.955	2.408	0.83

Table 3. Skeletal transverse changes at the lower border of the internal hard palate at ANS, Molar, and PNS in the axial plane at T1 (in millimetres).

	Mean	SD	Min	Max
ANS–ANS	5.34	1.54	2.68	8.79
MPSM	4.00	1.32	0.84	6.84
PNS–PNS	3.27	0.92	2.09	5.86

study was 73%. This is more than the average 67.25% of the dental crown expansion reported by Lin *et al.* and significantly more than the 43.34% reported by Choi *et al.* in their study of adult patients treated with a MARPE appliance [3, 10]. Our study also has a higher success rate than other bone-borne studies that were in adolescent populations [17, 23].

The alternative, and more invasive approach, to achieve maxillary expansion in adult patients is the SARME procedure. Kayalar *et al.* exhibited slightly greater expansion of the maxilla with a SARME procedure compared to the results of this study; however, a recent systematic review by Bortolotti *et al.* reported that whilst skeletal expansion with SARME was statistically significant, it was of low clinical significance and is instead mostly at the dental level [4, 24]. Furthermore, de Oliveira *et al.* compared adult patients undergoing MARPE or SARME, and showed that MARPE exhibited significantly greater expansion in the midface, palate, and posterior maxilla compared to SARME, illustrating the ability of mini-screw assisted appliances to achieve effective skeletal expansion [25].

Expansion in the coronal plane

In the coronal plane, expansion achieved at the dental level was more than that achieved at the skeletal level, illustrating a pyramidal-shaped pattern of expansion. Further to this, although the amount of expansion at the upper inter-zygomatic distance was not significant, a significant increase in the lower inter-zygomatic distance was found, further demonstrating a pyramidal configuration of expansion. These findings are consistent with the literature, which describes the resistance of the circum-maxillary sutures leading to a triangular pattern of transverse craniofacial separation during traditional RME and MARPE therapy with the apex towards the nasal cavity and the base at the level of the palatine processes [14, 16, 26–30]. Furthermore, although the use of pure bone anchored appliances should reduce this outward tipping since the location of the expansion appliance is still below the centre of resistance of the maxilla, this is unavoidable. Canterella *et al.* similarly found larger increases in the lower inter-zygomatic distance compared with the upper inter-zygomatic distance with the MSE appliance in late adolescent patients, concluding that the zygomaticomaxillary complex rotates outward with the centre of rotation located near the frontonasal suture [28]. In our study, transverse measurements between the left and right zygomatic arches also increased significantly, most likely due to the bi-cortical engagement of the mini-screws, promoting the lateral displacement of the zygoma. These changes illustrate that expansion extended to the mid-zygoma, however, did not extend to the frontozygomatic sutures, indicating that the Quad-expander appliance can successfully expand the maxilla and mid-zygoma in adult patients, however, does not have an effect on cranial structures.

Expansion in the axial plane

In the antero-posterior plane, the ratio between expansion at PNS and ANS was 61%, indicating a V-shaped pattern of opening of the MPS in the sagittal plane, with more expansion anteriorly. This is expected since there is less resistance from circum-maxillary sutures anteriorly than posteriorly. Winsauer *et al.* noted that the anterior location of the mini-screws in the Micro-4 appliance could also be the explanation for the V-shaped pattern of expansion achieved in these patients (54% less expansion posteriorly in their pilot study), and this would also be the case for the Quad-expander [7]. Our results are different to the MSE appliance that exhibits a more parallel type expansion of the suture, ANS to PNS ratio of 95.7% [16, 31]. Clement *et al.* suggested that the more posterior position of the jack screw, as well as the parallel and posterior placement of the four mini-screws with the MSE appliance, overcomes the resistance induced from the zygomatic buttress and thus is likely the reason for the more parallel pattern of expansion [16, 32]. Other studies, however, account the parallel expansion of the suture to be due to the bi-cortical and parallel placement of the mini-screws with MSE, offering a more even force distribution and greater skeletal anchorage [32]. It is important to note that variations in appliance design will alter the patterns of expansion depending on anchorage sites and stress distribution.

Tipping of dentoskeletal structures

Traditionally, dentoalveolar side effects with conventional RME include lateral bending of the alveolar bone as well as buccal tipping of the posterior anchor teeth [19, 33]. The attraction towards skeletally anchored expansion appliances is the notion that skeletal effects are maximized whilst unwanted dental side effects are minimized. The literature reports that bone-borne expansion appliances exhibit less buccal tipping of the first premolar and molar and greater buccal bone thickness compared with tooth-borne RME [34]. The angle of the alveolus at the first molar and first premolar in this study increased outwards by a mean of 1.26° and 0.23°, respectively, both that are negligible. The dental tipping as measured by the angulation change of the first premolar and molars is less than that of the alveolar housing tipping, suggesting a slight uprighting of the teeth within the alveolus, though these were not statistically significant. Furthermore superimpositioning of the maxilla was not undertaken to quantify the exact remodelling that has taken place. This is still in agreement with current literature, suggesting that pure bone-borne expansion eliminates the dental side effects of tipping due to the absence of direct force application to the teeth, and in fact exhibits uprighting of the posterior teeth instead [17, 23, 32]. As the maxilla expands, forces applied from the buccal musculature may impart force on the crowns of teeth preventing buccal tipping and promoting uprighting whilst reducing buccal bone thinning [10, 17, 18].

Limitations

The major limitations of this study are the retrospective design, short-term follow up, and lack of control group. Only patients who fulfilled the inclusion criteria and patients with pre–post radiographs with all landmarks/structures visible were included in the study. The small sample size also did not allow to make comparisons in the magnitude of suture opening, transverse, and angular measurements between males and females or between younger and older skeletally mature patients. Future studies could utilize this appliance design and protocol in a randomized clinical trial to compare to other expansion modalities and follow-up patients in the long term.

Conclusion

The Quad-expander, utilizing four mini-screws in the palate with a controlled force response guided expansion protocol, effectively produced significant increases in maxillary width in skeletally mature subjects. The expansion was V-shaped in the antero-posterior plane and pyramidal in the coronal plane, exhibiting expansion to the mid-zygoma level, however, not extending to the frontonasal suture or cranial structures. Dental side effects of posterior teeth tipping were avoided, and instead uprighting of the posterior teeth was experienced, illustrating that the Quad-expander is an effective appliance that can be used in skeletally mature populations without deleterious dental side effects. The stability of these results should be investigated in the long term.

Author contributions

Priyanka Ponna (Formal analysis [Lead], Investigation [Equal], Methodology [Supporting], Writing—original draft [Lead], Writing—review & editing [Supporting]), Nour Eldin Tarraf (Conceptualization [Lead], Data curation [Lead], Investigation [Equal], Methodology [Equal], Resources [Lead], Supervision [Supporting], Writing—original draft [Supporting], Writing—review & editing [Supporting]), Kerem Dalci (Formal analysis [Supporting], Investigation [Supporting], Writing—original draft [Supporting], Writing—review & editing [Supporting]), Benedict Wilmes (Investigation [Supporting]), Mehmet Ali Darendeliler (Investigation [Supporting], Supervision [Supporting]), and Oyku Dalci (Data curation [Supporting], Formal analysis [Supporting], Investigation [Equal], Methodology [Equal], Supervision [Lead], Writing—original draft [Supporting], Writing—review & editing [Lead])

Conflicts of interest

None declared.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Supplementary material

Supplementary material is available at *European Journal of Orthodontics* online.

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