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AAO Foundation Final Report Form
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Please prepare a report that addresses the following:

Type of Award, Orthodontic Faculty Development Fellowship Award

Name(s) of Principal Investigator(s): Ayman Al Dayeh

Institution: University of Tennessee Health Science Center

Title of Project: Maxillary Expansion in Tooth-Borne Versus Bone-Borne Palatal Expanders

Period of AAOF Support (07-01-2017 extended to 06-30-2022):

Amount of Funding: 20,000

Summary/Abstract

The basic premise of the project is to assess, in real-time, the pattern and difference in sutural and alveolar bone loading between bone- and dental-borne palatal expanders (BRPE and DRPE), and to assess the impact of rapid palatal expansion on the mechanical properties of the zygomatico-maxillary suture (ZMS). Additionally, we aimed to assess the morphology of the intermaxillary suture using µCT and CBCT. Briefly, the study was performed ex-vivo using ~4-8 months old pig heads (n=28). The anterior part of the rostrum was cut to reduce the length of the suture to 44±6 mm, comparable to that of humans. Heads were dissected, and the midpalatal suture (MPS), ZMS, internasal suture (INS) and the alveolar bone (AB) adjacent to the

anchor teeth were exposed. A differential-variable-reluctance-transducer (DVRT) was installed across the MPS to measure sutural separation, and single-element strain gauges were installed at the remaining sites. BRPE and DRPE were placed and activated at one turn per minute for 30 turns. Each turn corresponded to 250 µm. Strains at the alveolar bone and the sutures and the separation of the MPS were measured in real-time. To study the effects of expansion on the mechanical properties of the ZMS, ZMS and surrounding bone were excised, wrapped in gauze saturated with 4% phosphate-buffered saline and stored frozen (-20^{0}C). On the day of the experiment, samples were thawed and mounted using screws into a custom-made mechanical testing machine. Samples were then loaded at 0.3 mm/sec until failure while the force and displacement were recorded at ~32 Hz. Sample dimensions were used to calculate the stress and strain. The stress strain curve was plotted and the following variables were measured: Young's modulus at 5, 10 and 20% strain, ultimate strength, loading force and strain at failure. Additionally, the reason of failure was documented as either failure at the suture (disarticulation of the ZMS) or zygomatic or maxillary bone breakage (ZMS stayed intact).

Successful expansion of the MPS was achieved in 69% of the BRPE subjects compared to 27% in the DRPE group ($p<0.05$). No difference in success rate between younger and older animals in each group. The average separation of the MPS was higher in the BRPE group (230 ± 109 µm per turn vs. 79 ± 61 µm, $p<0.05$) and the MPS opening was achieved at an earlier stage of expansion (14±4 vs. 24±5 turns) in the BRPE. The pattern of MPS separation suggests a stress buildup at the suture. In the BRPE group, minimal MPS separation was measured in the first 13 turns (44 ± 12 µm). This was followed by a sudden opening of the suture that measured 999 ± 161 µm in one turn, much higher than the 250-µm of screw activation. This was followed by sutural opening that was often higher than the amount delivered via expansion screw activation (350 ± 92 µm per turn). A similar pattern was noticed in the DPRE group; however, it was of a lesser magnitude (517 ± 280 µm). Interestingly, mild tensile deformation and/or opening of the suture (<300 µm) was seen in the failed experiments. Beside the expansion of the intermaxillary part of the MPS, visual examination of the heads that underwent successful RPE, showed various degrees of opening of the inter-palatine suture, especially in the BRPE group.

The strain noticed at the ZMS was mostly compressive in both groups. Higher magnitude was seen in the BRPE group (−3124 ± 2147 µε vs. −1781 ± 1872, NS). When reporting absolute strain, the magnitude of ZMS deformation was significantly higher in the BRPE group, (4462 ± 1872 µε vs. 2610 ± 2001 µε; $p<0.05$). The same turn that showed the sudden opening of the MPS resulted in a sharp increase in strain at the ZMS. This was much higher in the BRPE group compared to DRPE (−1032 ± 631 µε vs. −54 ± 281 µε, $P < .05$). In the DRPE, most of the compressive strain at the ZMS was generated before MPS opening while in the BRPE, most of the strains occurred during and after MPS opening. The strains at the INS were mostly compressive and comparable between the 2 groups (−1148 ± 1640 µε vs. −931 ± 2348 µε). Higher compressive strains were consistently recorded at the AB in the DRPE (−119 ± 75 µε vs. −7 ± 89 µε). Including the failed experiments show much higher strains at the AB in the DRPE compared to the BRPE (−186 ± 369 µε vs. −7 ± 89 µε, $P < .05$). Interestingly, in five of the failed

DRPE, excessive buccal tipping of the molars was visible, and in two of them, the molars were avulsed outside their alveolar bone.

Measuring the mechanical properties of the ZMS showed a non-linear relationship between the stress and the strain, consistent with a viscoelastic structure. The results showed that the ZMS is robust (failure force was > 500N) with increased level of interdigitation, stiffness and ultimate strength. While the ultimate strength of the suture was high (564±271 N), it was primarily due to increased surface area of the suture and the level of interdigitation of the maxillary and zygomatic bone. Calculating the ultimate strength of the suture relative to the surface area showed values (2.17±1.19 N/mm2), ~3-folds higher than those reported at the nasofrontal suture (0.7-0.9 MPa) in the same species comparable to those reported at the NFS in the same species. Rapid palatal expansion had limited effect on the mechanical properties of the suture. While a tendency of higher stiffness was seen in animals that underwent successful RPE (at 5% strain 3.8± 1.7 MPa vs. 3.2 ± 2.2 N/mm ^{2}), no statistical difference was found between the 2 groups in any of the variables measured.

Despite the limited difference in the mechanical properties of the ZMS between expanded animals and untreated controls, the pattern of failure during the tensile testing was different. In the group that underwent successful expansion, disarticulation of the zygomatic and maxillary bones was noticed in most of the animals studied (8 out of 9) compared to 55% (6 out of 11) in the untreated controls group. Animal age has limited effect on the properties of the suture. The only difference between the age groups was the increased ultimate strength seen in the older age group regardless whether the animals received RPE.

Within the limitation of our study, our results suggest that BRPE is a more efficient form of expansion as demonstrated by the higher success rate, decreased alveolar bone strain and more skeletal expression of the expansion screw activation. Our mechanical data suggest that RPE had limited effects on the mechanical properties of the suture.

Detailed results and inferences:

1. If the work has been published please attach a pdf of manuscript: Parts of the work were published: Fox GC, Jones TA, Wilson JM, Claro WI, Williams RA, Trojan TM, **Al Dayeh AA.** Sutural loading in bone- versus dental-borne rapid palatal expansion: An ex vivo study. Orthod Craniofac Res.2020;00:1–8. https://doi.org/10.1111/ocr.12384.

2. Describe in detail the results of your study. The intent is to share the knowledge you have generated with the AAOF and orthodontic community specifically and other who may benefit from your study. Table, Figures, Statistical Analysis, and interpretation of results should be included: A pdf copy of the published manuscript is attached to this report

Respond to the following questions:

1. Were the original, specific aims of the proposal realized?
   Most of the original specific aims of the study were achieved. One of the original aims was to utilize CBCT scans of the head and μCT scans of section of the suture that were obtained

during rostrum reduction to determine if they can be used to predict the success of the expansion. Pilot analysis showed that the radiographic examination was inconclusive with great individual variation. As a result, this part of the project was abandoned, and animals were classified based on their dental age into early and late-mixed dentition.

2. Were the results published? Yes
    a. Fox GC, Jones TA, Wilson JM, Claro WI, Williams RA, Trojan TM, Al Dayeh AA. Sutural loading in bone- versus dental-borne rapid palatal expansion: An ex vivo study. Orthod Craniofac Res.2020;00:1–8. https://doi.org/10.1111/ocr.12384.
    b. Was AAOF support acknowledged? Yes
    c. If not, are there plans to publish? The mechanical properties of the ZMS were not reported in the above manuscript. We are planning to incorporate the findings into another project that deals with the mechanical properties of craniofacial sutures.
3. Have the results of this proposal been presented?
    a. If so, list titles, author or co-authors of these presentation/s, year and locations: "Sutural loading in bone- versus tooth-borne palatal expansion: An ex vivo study." Ayman Al Dayeh, 2019 AAO annual session, Los Angeles, CA.

    "Sutural loading in bone- versus tooth-borne palatal expansion: Ex vivo study." Wilson and Al Dayeh, Poster, AADR 2020

    b. Was AAOF support acknowledged? Yes
    c. If not, are there plans to do so? If not, why not? We are hoping to present on the relation between the mechanical properties of the ZMS and maxillary expansion in future meetings. Due to the delays caused by the COVID-19 pandemic, no clear timeline is yet established
4. To what extent have you used, or how do you intend to use, AAOF funding to further your career? Funding from the AAOF played a crucial role in identifying and pursuing my research interests and to develop my career in academia. I plan to seek AAOF support in the future to help me in pursuing my research endeavors and clinical and teaching skills development opportunities.

Accounting for Project; (i.e.): The budget allocated to this project has been fully utilized.

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ORIGINAL ARTICLE

Orthodontics & Craniofacial Research WILEY

Sutural loading in bone- versus dental-borne rapid palatal expansion: An ex vivo study

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American Association of Orthodontists Foundation, Grant/Award Number: Orhan C. Tuncay Teaching Fellowship Awards

Abstract

Objectives: To measure and compare the success rate and strains generated during bone- (BRPE) and dental-borne rapid palatal expansion (DRPE) at the alveolar bone, zygomaticomaxillary (ZMS) and internasal (INS) sutures. Additionally, the magnitude and the pattern of midpalatal suture (MPS) separation in the 2 groups was assessed.

Setting and Sample Population: The study was performed ex vivo using 28 pig heads.

Materials and Methods: Heads were dissected, and the MPS, ZMS, INS and the alveolar bone were exposed. A differential-variable-reluctance-transducer (DVRT) was installed across the MPS, and single-element strain gauges were installed at the remaining sites. Expanders were placed and activated at one turn per minute for 30 turns. Strains at the alveolar bone and the sutures and the separation of the MPS were measured.

Results: Successful expansion of the MPS was achieved in 69% of the BRPE subjects compared to 27% in the DRPE group. The average separation of the MPS was higher (230 ± 109 µm per turn vs. 79 ± 61 µm) and the MPS opening happened at an earlier stage of expansion in the BRPE. Higher strains at the ZMS were seen in the BRPE group, while higher strain at the alveolar bone was found in the DRPE group.

Conclusions: The BRPE group demonstrated more successful and effective expansion of the MPS. Higher strain was found at the alveolar bone in the DRPE. A tendency for higher strain at the ZMS was noticed in the BRPE.

KEYWORDS

bone-borne palatal expansion, circummaxillary sutures, dental-borne palatal expansion, miniscrews

1 | INTRODUCTION

Transverse maxillary deficiency is a prevalent skeletal problem and has been associated with impairments in oral function and breathing.[1] As first described by Emerson Angell in 1860,[2] rapid palatal expansion has been the treatment of choice for transverse maxillary deficiency. Typically, it is accomplished using dental-borne rapid palatal expansion (DRPE), using maxillary teeth as a point of force application. This separates the midpalatal suture (MPS) resulting in bone formation along the sutural edges.[3,4] The expansion force associated with expansion is relatively high (~100N),[5] which when delivered to the teeth rather than the bone itself, results in undesired

Gavin C. Fox and Thomas A. Jones Joint first authors.

side effects, including tipping of the anchor teeth and alveolar bone, possible dehiscence, and long-term instability.[5-9]

Maxillary expansion is dependent on the maturation status of the intermaxillary suture.[10] As patient age, the suture increases in complexity and eventually fuses.[11] The increase in sutural interdigitation is associated with increased resistance to expansion. Currently most clinicians limit expansion to younger ages, typically before 13-15 years of age.[12] However, the relation between sutural interdigitation and age shows great variability.[11,13,14] For example, in a study on human cadavers,[15] fusion of the intermaxillary suture was found in patients ranging from 15 to 19 years old; however, some patients showed sutures with no signs of fusion at the age of 32. This suggests that the failure of DRPE in some young adults is due to improper force delivery rather than total fusion of the suture. In DRPE, if the sutural tensile strength is greater than that of the alveolar bone, most of the distraction force will be concentrated on the teeth, resulting in their tipping.[16] Theoretically, delivering the distraction force more directly to the suture will result in more efficient force concentration with the potential for expansion of the more interdigitated sutures.

With the advent of temporary skeletal anchorage devices (TSADs), bone-borne palatal expansion (BRPE) has become an alternative treatment option for transverse maxillary deficiency.[17] The premise of BRPE is to apply expansion force directly to the maxilla using TSADs that are placed in the palate on both sides of the MPS. Bypassing teeth and applying the expansion force directly to the bone allow the separation of more interdigitated MPS,[18,19] while limiting the dental side effects.[6,20,21]

Besides its effects on the MPS, DRPE results in lateral bending of the alveolar bone and mild strain and widening of the circummaxillary sutures.[22,23] The strains at the sutures are of particular interest because bone formation could be stimulated resulting in changes in skull morphology.[24] Additionally, it has been suggested that maxillary expansion might facilitate maxillary protraction.[25,26] Despite the increasing use of BRPE, its effects on the alveolar bone and circummaxillary sutures remain largely unknown. Most of the knowledge on this topic comes from finite element analysis computing models[27-30] with no direct measurement of strains to validate computer findings.

The aims of the present study were to (1) assess the success rate of BRPE and DRPE and (2) measure and compare the strains at the zygomaticomaxillary suture (ZMS), internasal suture (INS) and at the alveolar bone in the two groups during expansion. Additionally, the difference in MPS separation between the two groups was assessed. The null hypothesis was that there is no difference in the success rate and magnitude of sutural deformation between BRPE and DRPE.

2 | MATERIALS AND METHODS

The study was performed ex vivo on 28 pig heads obtained from a local abattoir, and the exact age and sex of the animals are unknown. All the animals were in various stages of mixed dentition, and based on the status of teeth eruption, the animals were ~4-8 months old. Pigs were chosen because their maxillary articulations and circummaxillary suture arrangement are analogous to those of humans. However, the midpalatal sutures in pigs are longer. Thus, the anterior part of the rostrum was cut to reduce the length of the intermaxillary suture to ~44±6 mm, comparable to that in humans. The pigs were randomly assigned to dental- and bone-borne expansion groups. The heads were stored at −20°C and thawed at room temperature ~18 hours prior to use.

The palatal mucosa was stripped to expose the palate and the MPS. Alginate impressions were taken for the fabrication of custom-made palatal expanders. Leone rapid palatal expansion screws (Great Lakes Orthodontics, MI) were used. For the DRPE, custom bands were fitted to the first permanent molar and soldered to the posterior arm of the expander. The anterior arm of the expander was bent to passively adapt to the lingual surface of the remaining teeth (Figure 1A). Metal mesh was spot-welded inside the bands to improve retention. The expanders were cemented using Panavia V5 cement (Kuraray America, NY) following manufacturer instructions. For the BRPE, the arms of the expander were bent to form a circle that tightly fit a 2 × 13 mm titanium miniscrews (KLS Martin America, FL), and silver solder was used to close each circle (Figure 1B). Because the expander key supplied by the manufacturer deformed in the pilot experiments, heat-treated 0.040" stainless steel wires were used to activate the expanders.

The INS, the right and left alveolar bone and ZMS were exposed. The bone surface was cauterized, degreased and then dehydrated using 100% ethanol. Sutures were protected with Teflon tape. Seven single-element strain gauges (Vishay Precision Group, Wendell, NC)

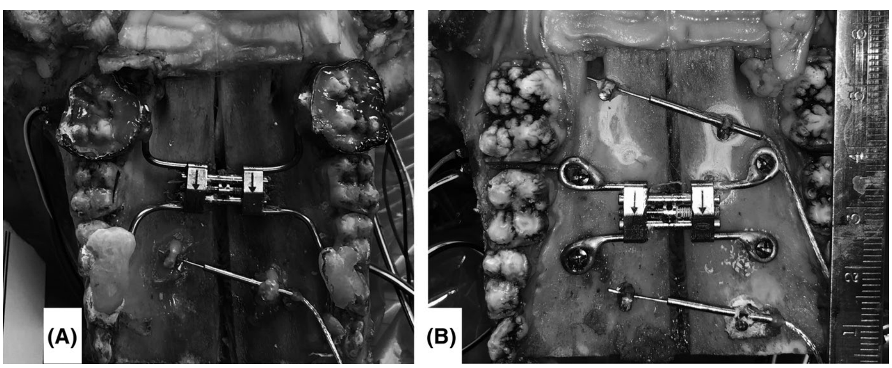

FIGURE 1 Occlusal view of the animals' palate illustrating the DVRT location and the expander design for the (A) dental-borne rapid palatal expander (DRPE) and (B) bone-borne rapid palatal expander (BRPE). Initially, we attempted to place an anterior and posterior DVRTs in the palate. However, because of the limited space, especially in the DRPE, only one DVRT was placed

were installed as follows: four were installed bilaterally on the buccal surface of the maxillary alveolar bone, 2 mm apical to the alveolar bone margin at the level of the first molars and first premolars in a dorsoventral direction, two were installed bilaterally across the ZMS and one gauge was installed across the INS using a cyanoacrylate-based glue (M-Bond 200, Vishay). The long axes of the sutural gauges were perpendicular to the long axis of the suture. One differential variable reluctance transducer (DVRT, LORD Microstrain, VT) was installed across the midpalatal suture. Because of the variability in the transverse dimension of the maxilla, the DVRT was installed at ~ 30° to the long axis of the MPS to accommodate the animals with narrow maxilla (Figure 1).

DVRTs measure linear deformation at ~1.5 µm resolution, while strain gauges measure deformation in microstrain ($(\Delta L/L0)^{*}\ 10^{6)}$).

The expanders were activated one turn (~250 µm) every minute for a total of 30 turns. At the end of expansion, specimens with greater than 1 mm of MPS separation were categorized as successful expansion, while those with less than that were categorized as failed expansion. This threshold was established because separation that is less than 1 mm is clinically insignificant and hard to confirm visually.

The DVRT and strain gauge signals were captured and recorded using a V-link wireless transmitter and the associated Node Commander© software (LORD MicroStrain, VT). The resultant data files were analysed using AcqKnowledge software 4.0 (BIOPAC Systems, CA). The following variables were measured: strain at the alveolar bone and at the sutures (µε) and separation of the midpalatal suture (µm). Due to the potential complexity of the strain pattern and the limitations associated with the use of single-element strain gauges, both 'total strain' (the sum of strains generated during each turn) and 'total absolute strain' (the sum of absolute values of strains generated during each turn) are reported. Because of the great overlap in the strain recorded at the anterior and posterior alveolar bones and to avoid reporting redundant data, only posterior alveolar strain is reported.

2.1 | Statistical analysis

Data were analysed using the nonparametric chi-square and Mann-Whitney U (MWU) test with SPSS software (v. 25, IBM, Armonk, NY).

3 | RESULTS

Of the 13 subjects in the BRPE group, successful expansion was seen in 9 (69%), while in the DRPE group, successful expansion of the MPS was seen in 4 out of the 15 subjects (~27%) (*P* = .03, chi-squared test). The causes of failure in the BRPE group included deformation of the expander (n = 1), breaking of the solder joint and/or miniscrews (n = 2) and miniscrews going through the palatal bone (n = 1). The causes of failure in the DRPE group included bonding cement failure (n = 3), excessive tipping of anchor teeth (n = 3), excessive tipping of teeth with some expander deformation (n = 2), expander deformation (n = 1), no clear reason (n = 1) and the reason of failure not recorded (n = 1). Only data from the successful expansion experiments are reported except for the strain at the alveolar bone where data from all experiments are reported due to their potential clinical relevance.

Higher average separation of the MPS was seen in the BRPE (230 ± 109 µm per turn, ~94% of screw activation) compared to DRPE (79 ± 61 µm, ~32% of screw activation) (*P* = .03, MWU test).

Differences in the magnitude and time course of MPS separation between the BRPE and DRPE were noted (Figure 2). In the BRPE, minimal sutural separation was measured in the first 14 turns (44 ± 12 µm). This was followed by a sudden surge in the DVRT reading that corresponded to cracking and opening of the MPS (999 ± 161 µm in one turn) (Figure 3). It is important to note that this initial separation is significantly greater than the 250-µm screw activation turn. After the surge, the MPS continued to separate at a magnitude slightly higher than that created by the screw activation (350 ± 92 µm), suggesting that resistance to expansion disappeared after the surge. A similar pattern was noticed in the DPRE group; however, when compared to the BRPE, the surge was of a lesser magnitude (517 ± 280 µm) and happened later (turns 24 ± 5). The average amount of MPS separation before and after the surge in the DRPE group was 25 ± 18 µm and 278 ± 67 µm, respectively. The DVRTs recorded only mild separation of the suture in the failed experiments (296 ± 224 µm).

RPE resulted in overall compression at the ZMS (Figure 4). Although the magnitude of sutural deformation was higher in the BRPE, it was not statistically significant (−3124 ± 2147 µε vs. −1781 ± 1872). However, when reporting absolute strain, the magnitude of sutural deformation was significantly higher in the BRPE group, (4462 ± 1872 µε vs. 2610 ± 2001 µε; *P* = .05, MWU). Like the MPS, strain at the ZMS consistently displayed a sudden surge in strain gauge recording that coincided with surge recorded by the MPS DVRT (same turn). The ZMS surge was significantly higher in the BRPE group (−1032 ± 631 µε vs. −54 ± 281 µε, *P* < .05 MWU). Interestingly, in the DRPE most of the compressive strain at the ZMS was generated before the surge, while in the BRPE, most of the strains occurred during and after the surge (Figure 4C).

The strains at the INS were mostly compressive and comparable between the 2 groups (−1148 ± 1640 µε vs. −931 ± 2348 µε). Absolute strain was slightly higher in the BRPE; however, the difference was not statistically significant (3799 ± 3588 µε vs. 2770 ± 2267 µε).

Higher compressive strains were consistently recorded at the alveolar bone in the DRPE (−119 ± 75 µε vs. −7 ± 89 µε); however, this difference did not reach statistical significance. When the failed dental expansion experiments were included, significantly higher strain was present in the DRPE group (−186 ± 369 µε vs. −7 ± 89 µε; *P* < .05 MWU) (Figure 5).

4 | DISCUSSION

In this study, we report, for the first time, the deformation of the alveolar bone, intermaxillary, internasal and zygomaticomaxillary sutures during BRPE and compare them to the deformation during

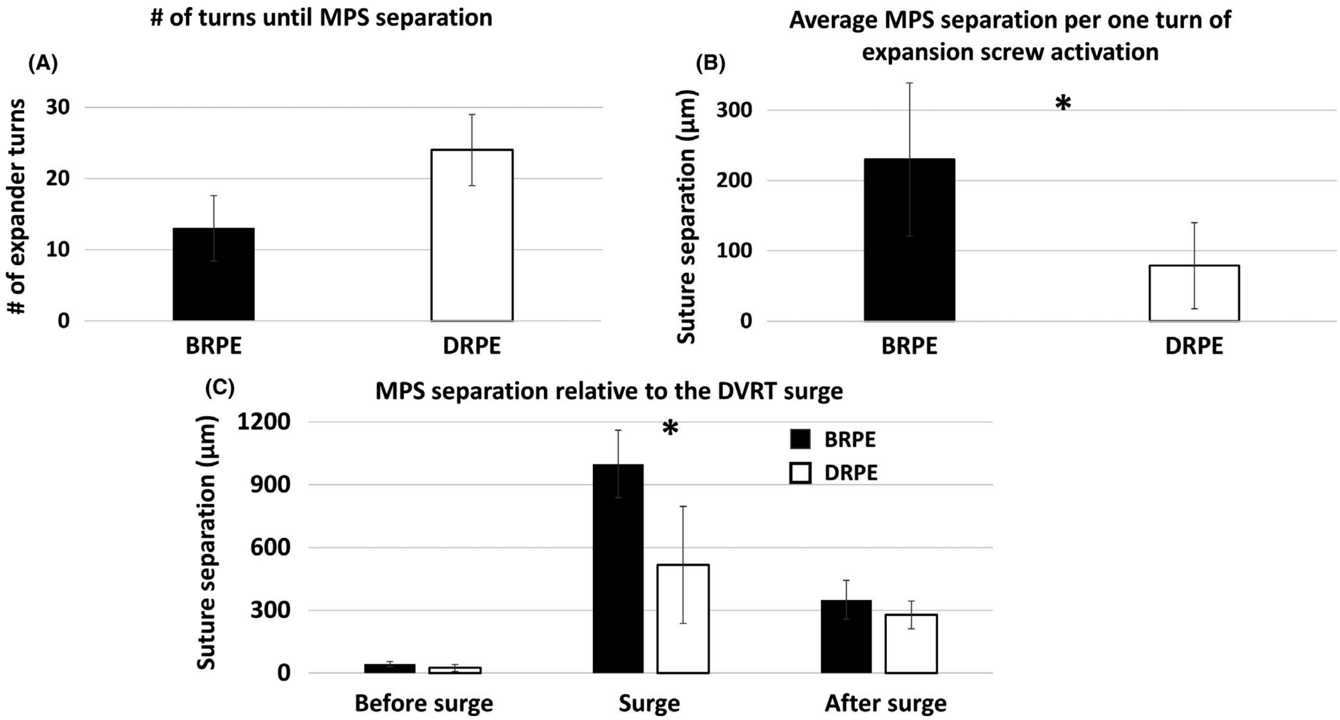

FIGURE 2 A, Difference in number of turns to produce midpalatal suture (MPS) separation between BRPE and DRPE, (B) difference in average MPS separation per one turn of expansion screw activation between BRPE and DRPE, (C) differences in MPS separation relative to the DVRT surge (MPS opening) between BRPE and DRPE. Error bars correspond to standard deviation. *Statistically significant. *P* < .05, Mann-Whitney *U* test

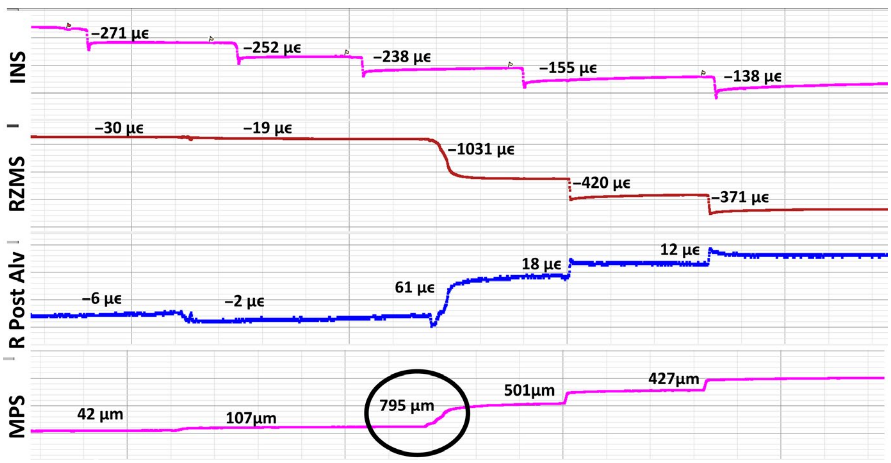

FIGURE 3 Example AcqKnowledge® recording from one of the BRPE subjects displaying the deformation recorded at the midpalatal suture (MPS, DVRT), right zygomaticomaxillary suture (RZMS), internasal suture (INS), right posterior alveolar bone (R post. alv.). The numbers illustrate the deformation per turn of the expander activation (MPS DVRT: µm, strain gauges: µε). Because of the figure scaling, the deformation at some of the structures might be hard to see on the graph. The surge in the DVRT recording is noted with a black circle. The surge in the DVRT recording was associated with a surge in strain gauge recording at the ZMS and R post-Alv but not the INS. In some animals, some delay between the expander turn and the suture separation was present

DRPE. Additionally, we provide a detailed observation of the events happening during expansion at the MPS and ZMS. Our results, however, should be interpreted with care as the study suffered some limitations, mainly due to the sample size in the DRPE, the ex vivo nature of the study, the use of strain gauges to measure alveolar bone strain and the lack of knowledge of the status of MPS maturation in the animals studied. While 9 of the 13 heads in the BRPE displayed successful expansion, only 4 out of 15 heads in the DRPE showed successful expansion. The low success rate in the DRPE, combined with the high individual variability, may have reduced the power to detect some of the differences between the two groups. Nonetheless, our data illustrate some differences between the two groups in the magnitude of strain and its timing relative to the expander activation. Because of the ex vivo nature of the study, we

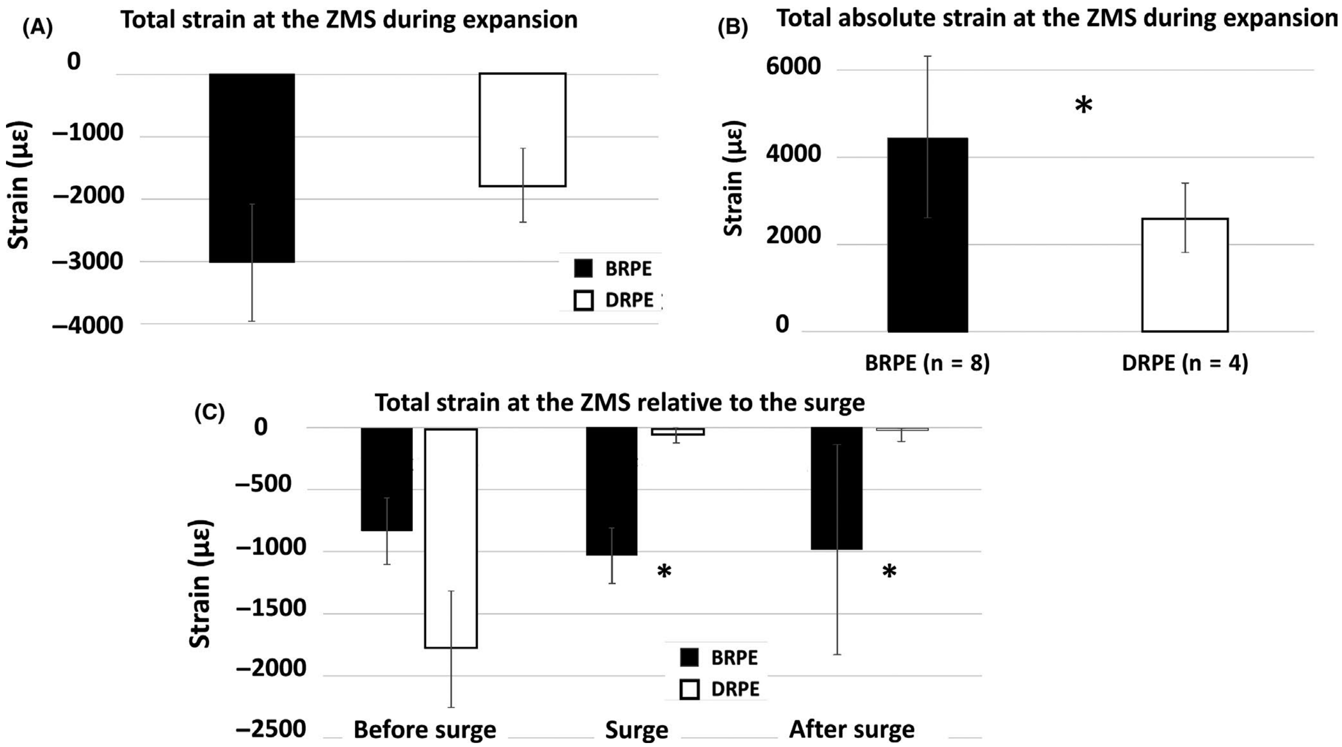

FIGURE 4 A, Difference in total strain at the ZMS during expansion between BRPE and DRPE, (B) difference in absolute strain at the ZMS during expansion between BRPE and DRPE, (C) differences in total strain at the ZMS during expansion relative to the surge (MPS opening). Error bars correspond to standard error of the mean. *Statistically significant. $P < .05$, Mann-Whitney U test

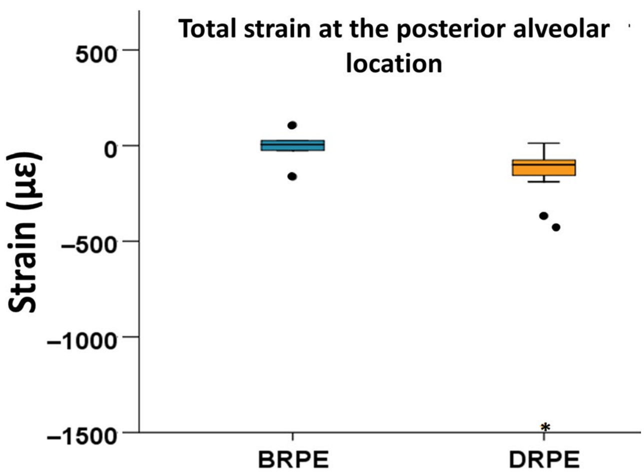

FIGURE 5 A boxplot plot illustrating the difference in strain at the posterior alveolar bone between the BRPE and DRPE. The failed DRPE was included. The box represents the interquartile (IQ) range. The whiskers correspond to 1.5 times the IQ range. Black circles are the values that were between 1.5 and 3 times the IQ range. The asterisk corresponds to one case that was more than 3 times the IQ range (one of the animals in which the molars were displaced out of the socket due to the DRPE activation)

are only reporting the mechanical deformation of the sutures during expansion with no information on the biologic impact of such loads. Furthermore, our expansion protocol of one turn every minute is greatly accelerated above the protocol typically used in the clinical setting, where expanders are activated at 1-4 turns a day. This acute loading might have prevented the associated tissues from absorbing and adapting to the expansion loads. However, it was necessary to prevent the samples from decaying during the experiments. The measured deformation might have also been affected by stripping of the palatal mucosa, an approach that was necessary for proper fabrication and installation of the expanders. Another limitation was introduced by using single-element strain gauges. While strain gauges are accurate in recording the deformation along their long axis, they cannot differentiate between axial compression and lateral bending. Additionally, torsional strain is simplified as compression or tension based on the location of the gauge. To limit the impact of this shortcoming, the strains were reported as 'total' and 'total absolute' strain. While the level of midpalatal sutural maturity in our sample is not known, the animals were of comparable dental age and were randomly assigned to either DRPE or BRPE rendering our comparisons valid. We believe that the sutures were in an advanced stage of interdigitation, probably compared to late-teen humans. This was supported by the high resistance to expansion in our experiments as evidenced by bonding cement failure, teeth avulsion, mechanical deformation of the expanders and activation keys and breakage of solder joints and titanium miniscrews in some of the experiments.

A retrospective study by Rojas *et al* compared the success rate of DRPE and BRPE in patients with an average age of 18 ± 5.5 years using CBCT.[31] Successful expansion was observed in all the BRPE patients compared to only half of the DRPE subjects. A similar finding was described by Choi *et al* [32] who reported an 87% success rate of BRPE in 69 adult patients (20.9 ± 2.9 years).[32] In a study on four 3-month- and four 6-month-old domestic pigs, Sun et al [23] reported that DRPE resulted in successful MPS separation in all the young group and in 50% of the 6-month groups. The present study aligns with the previous literature showing a higher success rate with the BRPE group and further suggest that the level of sutural maturity in our sample was comparable to those of late teens/ early adults.

Real-time observation of the MPS separation revealed significant differences in the magnitude, timing and pattern of separation between BRPE and DRPE. The magnitude of the MPS separation in the DRPE corresponded to only 32% of the screw activation. This coincides with clinical reports suggesting that sutural opening in DRPE patients amounted only to 20%-50% of screw activation,[33] and agrees with a previous pig study that showed ~2.2 mm increase in intermolar width after 5 mm of expander activation (measurement of suture separation was not reported).[23] On the other hand, MPS separation in the BRPE corresponded to 94% of screw activation. Another difference between the two groups was in the timing of MPS opening. In the BRPE group, the opening happened early in the experiment (~10-14 turns), while in the DRPE, the MPS opening was only noticed towards the end of our expansion protocol. These findings suggest that BRPE provides more effective and efficient form of palatal expansion. The differences between the 2 groups can be attributed to the differences in anchorage and the point of force application. In the DRPE, expansion force is applied through the teeth, and some of the expansion force will be dissipated by the PDL and through dental tipping.[5-9,16] This explains the excessive strains recorded at the alveolar bone and the delayed MPS opening in the DRPE. Additionally, the attachment points of the expander and the anchor teeth are vertically and laterally farther from the MPS, which will potentially result in less efficient mechanical loading of the suture. On the other hand, BRPE is applied more directly across the MPS, resulting in more effective loading of the suture, that could explain the higher success rate and more effective expansion in this group. Previous studies have suggested that BRPE results in more parallel separation of the suture when compared to the DRPE.[34]

The pattern of MPS separation in the BRPE was particularly interesting. Minimal separation (<100 μm) was noticed during the first few turns. This was followed by a turn resulting in a sudden ‘surge’ of sutural separation that was ~4 times greater than that delivered by a single-screw activation. A similar pattern was noticed in the DRPE, but to a lesser magnitude. After the surge, the MPS continued to separate at a magnitude higher than the amount of expansion screw activation in both groups. This pattern suggests that stresses generated by screw activations were stored, either in the bone (BRPE) or the dentition (DRPE). Once the suture opened, the stored stress was released in the form of sudden sutural separation that was significantly higher than the 250 μm delivered by one turn of the screw activation. The fact that the sutural expansion proceeded with no resistance after the surge suggests that this moment corresponded to the breaking of the MPS. Often accompanied with an audible cracking and after significant loading (>10 turns) suggest that the surge is a result of the breakage of the sutural interdigitation rather than a torn sutural ligament.

Interestingly, the DVRTs recorded mild tensile deformation of the MPS (<300 μm) even in the failed experiments. This deformation can be attributed to mild separation of the suture and tension of the bone between the DVRT arms. This suggests that the MPS was loaded in the failed experiments, but the load was insufficient to open the suture. The effects of stored stress in failed BRPE need to be thoroughly investigated as it might result in determinantal effects on the integrity of facial bones.

Previous literature reporting on the distribution of stresses to the craniofacial complex and circummaxillary sutures with BRPE and DRPE is mostly limited to finite element analysis (FEA) studies and has demonstrated varying and often conflicting results. For example, while some studies reported no significant difference in the stress distribution of the zygomaticomaxillary suture between the two groups,[28] others have reported that the stresses generated by DRPE were considerably less than that of BRPE.[29,34]

The inconsistencies in the FEA studies can be attributed to the complexity of sutural morphology and highlight the need for experimental findings to support computer stimulation. As Leonardi et al[35] stated, ‘it's reasonable to assume that compression, shear and tension forces may coexist in the same suture at different sites’. Considering that each suture has a complex morphology and experiences both tensile and compressive stresses, we decided to report the polarity (total) and overall magnitude (total absolute) of strain. Overall, the present study observed a tendency for higher compressive and absolute strains at the ZMS in the BRPE group. The discrepancy between the measured compressive (total strain) and absolute total strain supports the complexity of bone loading during expansion and suggests that in addition to compression, torsional and/or bending loads were present and higher in the BRPE.

Overall, we observed more compressive strain at the ZMS in the BRPE group, but the DRPE group demonstrated a larger value when considering the total strain before the surge. One explanation for this simply relates to the number of turns required to separate the suture in the DRPE group. The greater number of turns required with the DRPE allowed more time for the stress to build across the ZMS. However, when looking at the average strain per turn, the DRPE animals still displayed higher compression before the MPS opening, while the opposite was seen in the BRPE group. One potential reason is in the point of force application. In the DRPE group, the force was applied at the molars which are closer to the ZMS resulting in an earlier loading of the suture. This suggests that once the MPS separated in the BRPE, the expansion load was transferred to the ZMS resulting in excessive compression of the sutures as evidenced by the coincidence of the surges in the DVRT and strain gauge recordings at the MPS and ZMS, respectively. Previous studies suggested that strain at the ZMS during RPE might facilitate maxillary protraction by loosening the suture.[36,37] The high level of strain at the ZMS during BRPE might have significant effects on the mechanical properties of the suture and warrant further investigation.

An ex vivo study on DRPE using fresh pig heads found that strain at the sutures was generally greater than at the alveolar bone.[23] Results from the present study also found that there was less strain expressed at the alveolar bone when compared to the ZMS and INS, although it should be noted that strain gauges are limited in measuring lateral strain (such as alveolar bone bending). Nonetheless, our results showed that strain at the posterior alveolar bone was consistently higher in the DRPE, especially when failed DRPE was added. Our results were comparable to those by Sun et al [23] using rosette strain gauges in their 6-month-old pigs. Interestingly, in five of the failed DRPE, excessive buccal tipping of the molars was visible, and in two of these experiments, the molars were avulsed outside their alveolar bone. This agrees with clinical findings that showed more dental tipping in the DRPE[38,39] and highlights some of its limitations, especially when MPS opening is not achieved resulting in the concentration of expansion force on the dentoalveolar structure.

5 | CONCLUSIONS

Within the limitations of the study, our conclusions are

- BRPE provides a successful and efficient method for MPS expansion
- A tendency for higher strain at the ZMS in the BRPE compared to the DRPE
- Higher compressive strain at the alveolar bone in the DRPE compared to the DRPE

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in the present article.

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