Journal of Taibah University Medical Sciences (2022) 17(3), 401–407

Taibah University

Journal of Taibah University Medical Sciences

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Comparative evaluation of transpalatal arch and vertical holding appliance at different heights

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Received 2 August 2021; revised 10 November 2021; accepted 13 November 2021; Available online 23 December 2021

الملخص

أهداف البحث: تظل الطرق الفعالة للسيطرة على خلل التنسج العمودي مصدر قلق لأطباء تقويم الأسنان. تهدف هذه الدراسة إلى مقارنة الضغط على الأضراس العلوية الأولى مع تغيير ارتفاع وسادة الاكريليك الحلقية لجهاز قوس الحنك وجهاز التثبيت الرأسي اثناء البلع بإستخدام تحليل العناصر المحددة.

طرق البحث: تم التقاط تصوير مقطعي للرأس والرقبة لمرضى أسنان الفك العلوي المستوية والمحاذية لإعادة البناء ثلاثي الأبعاد. تم بناء ستة نماذج تتكون من الفك العلوي مع الأضراس ورباط دواعم السن المحيطة مع ارتفاعات مختلفة من وسادة الاكريليك الحلقية للأجهزة. تم تطبيق قوة مقدارها 112 جم / سم^{٢} على وسادة الاكريليك الحلقية لكلا الجهازين لمحاكاة متوسط ضغط اللسان. تم تحديد توزيع ضغط التشويه الأقصى الواقع في رباط دواعم السن بسبب ضغط اللسان في منطقة العنق، والمنفرق، والشدقي الوحشي، والإنسي الشدقي، وقمم الجذر الحنكي. قام الأشخاص الذين يحتاجون إلى جهاز قوس الحنك وجهاز التثبيت الرأسي بمختلف الارتفاعات أثناء علاج تقويم الأسنان بتقييم مدى راحتهم مع الجهاز على مقياس النظير البصري.

النتائج: أظهر جهاز التثبيت الرأسي قيم ضغط أعلى على جميع ارتفاعات أرضية الحنك مقارنة بالارتفاعات المقابلة لجهاز قوس الحنك. وجد أن نموذج 8 مم من جهاز التثبيت الرأسي فعال بشكل خاص وظيفيا. كما كان ينظر إلى هذا الارتفاع على أنه مقبول من قبل معظم المرضى على مقياس النظير البصري.

الاستنتاجات: عندما تحفظ وسادة الأكريليك الخاصة بجهاز التثبيت الرأسي على مسافة 8 مم من قاع الحنك، فإنها تعزز الكفاءة الوظيفية للجهاز مع توفير راحة مقبولة للمريض.

الكلمات المفتاحية: الأضراس العلوية؛ جهاز قوس الحنك؛ جهاز التثبيت الرأسي؛ العنصر المحدد؛ ضغط.

Abstract

Objectives: An effective method for controlling vertical dysplasia remains a concern for orthodontists. This study aims to compare the stresses on the maxillary first molars while changing the height of the loop/acrylic pad of the transpalatal arch (TPA) and vertical holding appliance (VHA) during swallowing using finite element analysis.

Methods: Head and neck computed tomography (CT) of a patient with levelled and aligned maxillary teeth was taken for a three-dimensional reconstruction. Six models comprising the maxilla, molars, and surrounding periodontal ligament (PDL) with different heights of loop/acrylic pads of the appliances were constructed. A force of 112 g/cm^2 was applied to the loop/acrylic pads of both appliances to simulate the average tongue pressure. The distribution of von Mises stresses occurring at the PDL due to the tongue pressure was mapped at the cervical area, furcation, distobuccal, mesiobuccal, and palatal root apices. Separately, subjects requiring TPA and VHA at different heights during orthodontic treatment were asked to rate their comfortability with the appliance on the visual analogue scale (VAS).

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Peer review under responsibility of Taibah University.

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1658-3612 https://doi.org/10.1016/j.jtumed.2021.11.004

Results: The VHA demonstrated higher values of stresses at all heights from the palatal floor compared to the corresponding heights of the TPA. The 8 mm model of VHA was found to be functionally effective. This height was also perceived to be acceptable for most patients on the VAS.

Conclusions: The acrylic pad of VHA when kept at a distance of 8 mm from the palatal floor enhances the functional efficiency of the appliance with an acceptable comfortability for the patient.

Keywords: Finite element; Maxillary molars; Stress; Transpalatal arch; Vertical holding appliance

Introduction

Vertical dysplasia becomes a concern for orthodontists in diagnosis and treatment planning, even before the eruption of the maxillary first permanent molars. Such patients are particularly vulnerable to extrusion during treatment. Thus, an effective method to restrict the extrusion of the posterior teeth, or even intruding them, becomes necessary for the orthodontist to allow forward rotation of the mandible.[1,2]

The design of the contemporary transpalatal arch (TPA) follows the contour of the palatal mucosa, with its loop present in the middle of the palate. This facilitates correction of molar rotation, expansion, intrusion, distalization, stabilization, and anchorage.[1] Hata[3] based on his studies on Macaque monkeys stated that TPA can provide a vertical growth control, which is considered to be produced by the tongue pressure during deglutition and mastication.

Wilson[4] described the vertical holding appliance (VHA) to be useful in preventing extrusion of the maxillary molars. This appliance is a modification of the TPA with an incorporated acrylic pad, and hence makes use of the tongue pressure during swallowing to counteract the extrusion of the maxillary first permanent molars.

The tongue pressure that accompanies oral functions such as mastication, speech, and swallowing is exerted on the palate[5−7] and exhibits a range of 37−240 g/cm^2, with an average of 112 g/cm^2.[8] Kincaid[9] evaluated the frequency of deglutition to be anywhere between 15 and 75 times per hour, with the mode value being closer to 15. Such a frequency would subsequently amount to swallowing between 360 and 1800 times per day, therefore imparting a significant amount of tongue pressure on the palate. Both TPA and VHA make use of this pressure during swallowing or deglutition and mastication to stop the extrusion of molars and promote molar intrusion.

Exact data such as stress and strain on a biological structure by any experimental or analytical method is difficult to obtain owing to the complex interaction of the anatomical structures with their surrounding tissues.[10] Thus, keeping such a view in mind, a numerical method using a finite element model was incorporated in this study to map and compare the stresses on molars produced by tongue pressure on the VHA and TPA. This technique was developed by R. Courant in 1943 and was introduced into dentistry by Weinstein in 1976.[11]

The objective of the present study was to evaluate and compare stresses on the maxillary first molars due to tongue pressure on VHA as well as TPA during normal oral functions using a finite element model.

Materials and Methods

A three-dimensional reconstructed geometry of the maxilla was required for this study. Thus, a computed tomographic (GE Optima) scan of a healthy 27-year-old male patient was collected from Department of Radiology of Siksha 'O' Anusandhan University.

A total of 1024 layered slices with an approximate voxel size of $0.1 \times 0.1 \times 0.1$ mm were saved in DICOM format. All images were then stacked and imported into the medical image processing software MIMICS 10 (Technologielaan 15, B-3001 Leuven, Belgium). The 3-D model of the maxilla was reconstructed from the segmented layers based on dental morphology. Furthermore, to reduce the computational load, the finite element domain was made simple, including only the maxillary first molar along with the maxilla, Figure 1. The thickness of the PDL was kept uniform at 0.25 mm around the root of the first molars. Stainless steel VHA, as described by DeBerardinis et al.[1] was modelled using Solidworks software (Dassault Systèmes). Similarly, a stainless-steel TPA model was constructed using the same software. The three different heights of the loop/acrylic pad of TPA and VHA at 4, 8, and 12 mm were considered from the surface of the palatal floor at the midline between the right and left maxillary first molars. Hence, three separate 3-D models each of TPA and VHA were designed with different positions of the loop/acrylic pad (Figure 2 and Figure 3). A 4 mm interval in the height of the loop/acrylic pad of the appliances from the palatal floor was considered for the study because, with a reduced interval, the differences in stress patterns generated would not be very significant and might not prove helpful in obtaining a conclusive optimum height of the acrylic pad.

Once the model of the entire maxilla with the teeth from the alveolar crest to the nasal floor was generated, the extension was made up to 10 mm from the apex of the anterior teeth into the bone, making an artificial boundary of the maxilla. Further, all the reconstructed geometry along with the appliances were imported to the finite element package ANSYS (Swanson Analysis system, Canonsburg, PA). Tetrahedral solid elements (solid 90) were used to discretise the entire domain into 250,400 nodes and 140,635 elements, keeping the minimum edge length 1.5507e-007 m with an adaptive size function. All the contact surfaces were modelled as bonded because there was clinically no relative motion between the contacted surfaces.

The mechanical properties of the alveolar bone, TPA, and VHA were assumed to be elastic, isotropic, and homogeneous, as in previously published data.[11,12] Owing to the complex mechanical properties of PDL, a bi-linear elastic−plastic model[13−15] was used, as presented in Figure 4. The

Young's modulus and Poisson's ratio for the materials were taken from the literature[13,16] and are tabulated in Table 1. In this study, to simulate tongue pressure, a pressure of 112 g/cm^2 (equivalent to an average tongue pressure determined from previous experiments by Kydd et al.[5] and further quoted by Chiba et al.[8]) was applied to the loop/acrylic pad of both appliances. The top portion of the maxilla was provided with a fixed boundary condition.

In a real situation, the tongue pressure on the acrylic pad varies with the change in the acrylic pad's height. According to a previous study by Chiba et al.,[8] the difference in tongue pressure is minimal as we increase the height of the loop/acrylic pad above 4 mm. As we have considered the heights of the loop/acrylic pad to be 4 mm, 8 mm, and 12 mm, thus, to bring about a direct comparison of stresses at different locations while changing the heights of the acrylic pad, we had to consider the pressure exerted by the tongue to be constant to prevent any bias in the comparison of stress. The occlusal forces exerted on the maxillary first molars were not taken into consideration because they were persistent even when appliances were not used. Additionally, although the analytical deformations increased notably over time, the force and deformation characteristics were considered to be time-independent to simplify the process.

The distribution of stresses occurring at the PDL surface was mapped using the von Mises stress. Stresses were calculated at five different regions: cervical area, furcation, mesiobuccal, distobuccal, and palatal root apices (Figure 5) in all six models with heights of loop/acrylic pad of the appliances at 4, 8, and 12 mm from the palatal floor. The mean nodal von Mises stresses of the selected areas were then compared for the six models. Further, a pilot study with 30 subjects was undertaken clinically in parallel with this study to determine patient compliance with such varied heights of the loop/acrylic pad of the appliances. The subjects were selected from among patients undergoing treatment at the Department of Orthodontics and Dentofacial Orthopaedics at the Institute of Dental Sciences, Bhubaneswar, and requiring TPA/VHA during their treatment. The subjects were divided into 6 groups comprising five patients each (Group 1: TPA at 4 mm; Group 2: VHA at 4 mm; Group 3: TPA at 8 mm; Group 4: VHA at 8 mm; Group 5: TPA at 12 mm; Group 6: VHA at 12 mm). All the patients were asked to rate their comfortability on a visual analogue scale (VAS) from 1 to 10, where 1 represented the least comfortable and 10 represented the most comfortable.

Results

The palatal root apex demonstrated the highest stresses among the three roots of the maxillary first molars. Overall, the highest stresses were observed in the cervical area, followed by the furcation and palatal root apex. The mesiobuccal and distobuccal root apices generally demonstrated lower stress values. This pattern was observed in all the TPA and VHA models.

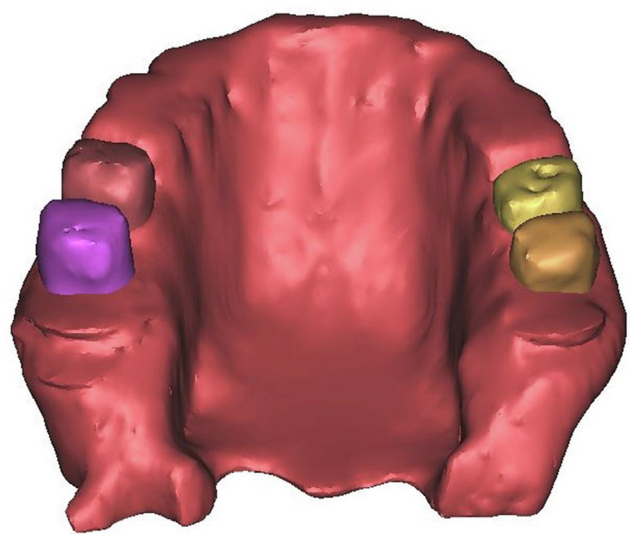

Figure 1: Reconstructed 3-dimensional geometry of the maxilla from the segmented layers.

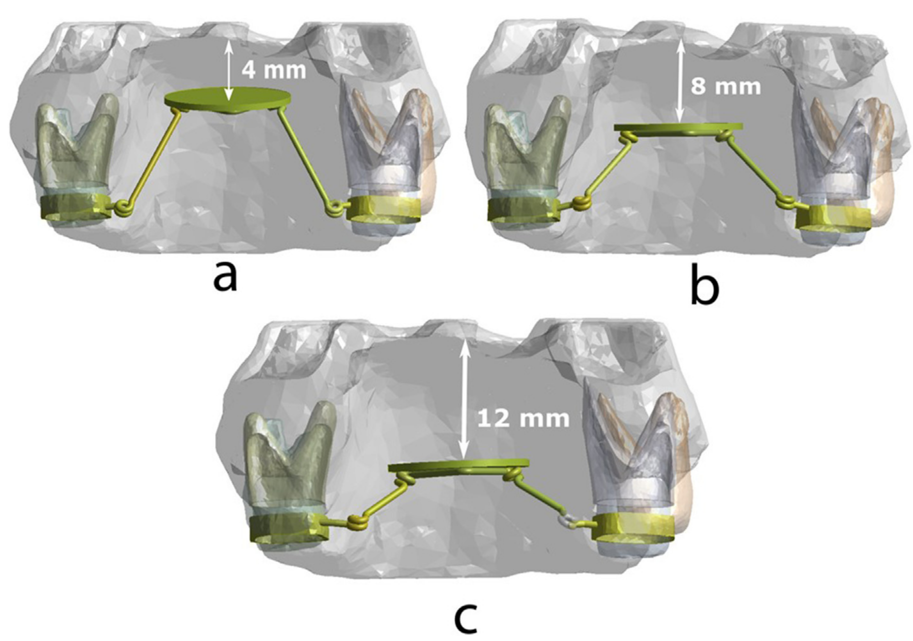

Figure 2: Vertical holding appliance with its acrylic pad at a height of (a) 4 mm, (b) 8 mm, and (c) 12 mm from the palatal floor.

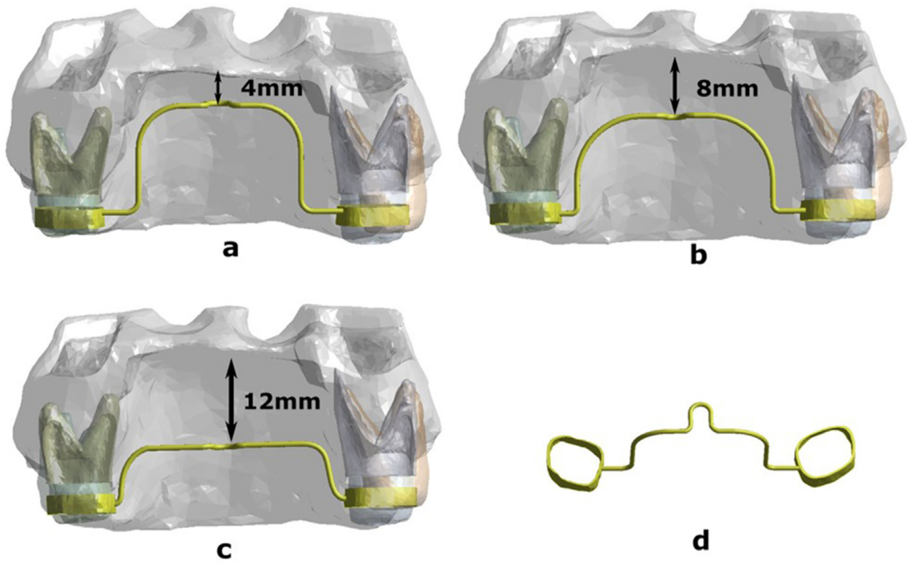

Figure 3: Transpalatal arch with its loop at a height of (a) 4 mm, (b) 8 mm, and (c) 12 mm from the palatal floor.

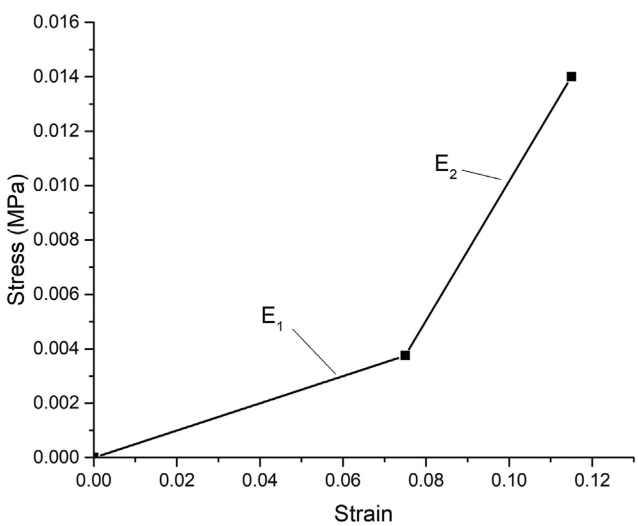

Figure 4: Bilinear property of periodontal ligament used in the models.

Among the TPA models, a higher overall stress was observed in the 4 mm model than in the 8 mm model. Similarly, there was a 33% reduction in the overall stresses generated when the 12 mm model was compared with the 8 mm model. A comparison of the 8 mm and 12 mm models demonstrated that the 12 mm model was able to generate higher stress values than the 8 mm model. Among the VHA models, the 8 mm model generated the highest stresses, followed by the 4 mm and 12 mm models.

When the TPA models were compared with their corresponding VHA models, each case showed that the stresses generated by the VHA model were much higher than those of the TPA models, as can be seen in Figures 6, 7, and 8. The 8 mm VHA model was found to generate up to 14 times more stresses compared to the corresponding 8 mm TPA model. Even the 4 mm model of VHA demonstrated three to six times higher values of stresses compared with the corresponding TPA models. A similar pattern was observed in the 12 mm model (Table 2).

The VAS scores of the subjects who were given the appliances demonstrated that the patients found the 4 mm TPA to be the most comfortable, followed closely by the 4 mm VHA, 8 mm TPA and 8 mm VHA. The subjects with 12 mm TPA and VHA models demonstrated the least level of comfort and acceptability (Table 3).

Discussion

Lundgren and Laurell[17] concluded that only 37% of the maximal occlusal force is utilised during normal oral functions such as swallowing and chewing, and that force

Table 1: Material properties of tooth and the supporting structures.

Material	Young's modulus (in MPa)[a]	Poisson's ratio
Tooth	20,000	0.3
Alveolar Bone	12,200	0.3
Periodontal ligament	Bilinear	0.3
Stainless steel	200,000	0.3
Acrylic	2700	0.35

[a] Young's modulus in megapascals.

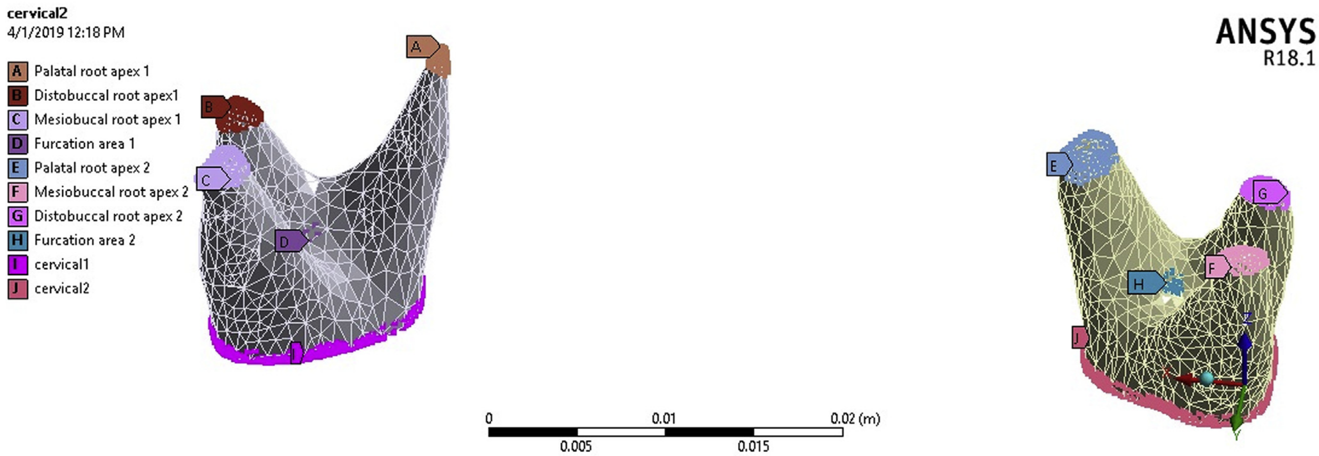

Figure 5: Stress was measured at five different regions of the periodontal ligament.

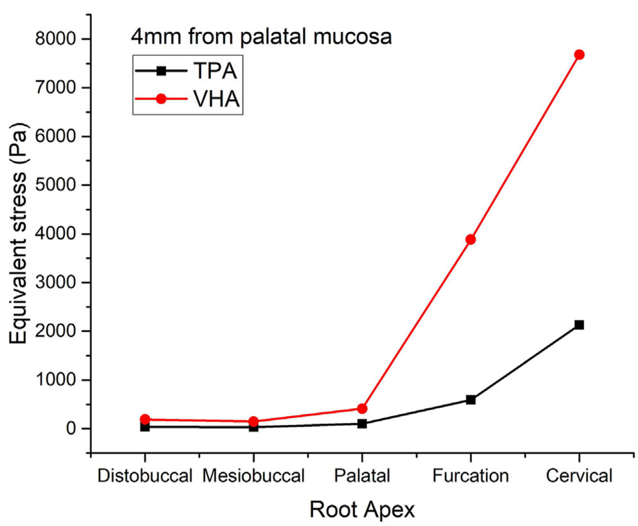

Figure 6: Comparison of equivalent stresses at all the areas when the loop/acrylic pad of the appliances are at 4 mm from the palatal floor.

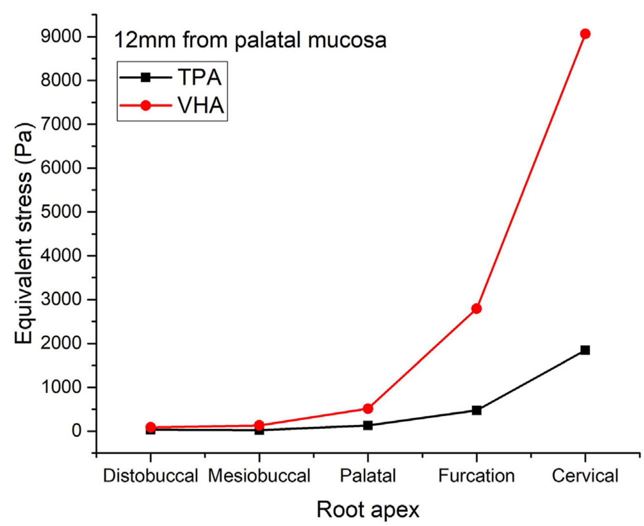

Figure 8: Comparison of equivalent stresses at all the areas when the loop/acrylic pad of the appliances are at 12 mm from the palatal floor.

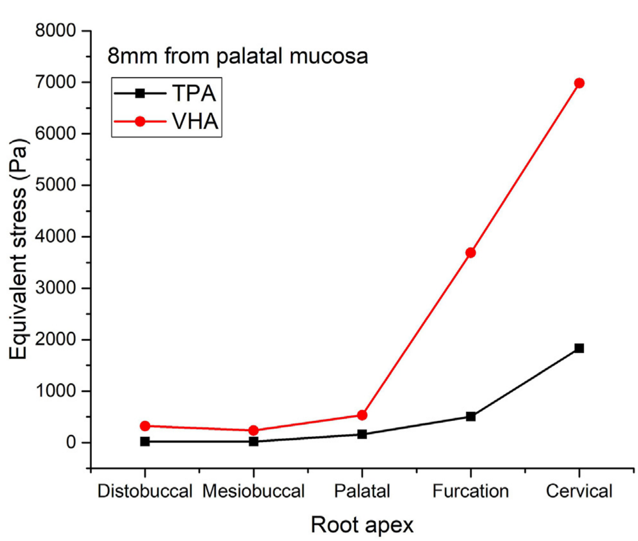

Figure 7: Comparison of equivalent stresses at all the areas when the loop/acrylic pad of the appliances are at 8 mm from the palatal floor.

is exerted for only 240 ms per cycle. Ferrato et al.[18] stated that occlusal forces are more pronounced in the mandibular molars than in the maxillary molars. According to a study by Romeed et al.,[19] the occlusal forces generated during normal oral functions are more concentrated at the buccal cervical region of enamel and decrease considerably at the dentin, cementum, and periodontal ligament. Furthermore, occlusal forces are persistent even when appliances are not used. These points prompted the authors to not consider occlusal forces in this ideal experimental situation.

The highest stresses were observed in the cervical area in all six models. This is because the cervical area is the closest point that we have taken from the point of application of force. This also explains the fact that the stress at the cervical area continued to increase as we shifted from 4 mm models to 8 mm, and finally to the 12 mm models. The highest stresses are usually observed at the point closest to the point of application of the force. Accordingly, the lowest stresses should be observed at the points which are furthest from the

Table 2: Comparison of von Mises stresses using TPA and VHA at a distance of 4 mm, 8 mm and 12 mm from the palatal mucosa.

Location	4 mm			8 mm			12 mm		
	Mean stress with TPA	Mean stress with VHA	Net stress increase with VHA	Mean stress with TPA	Mean stress with VHA	Net stress increase with VHA	Mean stress with TPA	Mean stress with VHA	Net stress increase with VHA
Distobuccal root apex	35.9	190.5	↑530.6%	21.6	322.2	↑1491.7%	32.6	86.1	↑264.1%
Mesiobuccal root apex	29.1	147.3	↑506.2%	22.1	235.4	↑1065.1%	23.3	130.3	↑559.2%
Palatal root apex	103.3	411.5	↑398.3%	162.5	535.3	↑329.4%	132	513.6	↑389.1%
Furcation area	590.1	3883.9	↑658.2%	506.8	3690.8	↑728.2%	477	2792.8	↑585.5%
Cervical area	2127.3	7678.7	↑360.9%	1827.4	6982.4	↑382.1%	1846	9062.8	↑490.9%
Net stress gain			**↑2454.2%**			**↑3996.5%**			**↑2288.8%**

Table 3: VAS scores of patients in terms of their comfort with the different heights of loop/acrylic pad of the appliances.

Height of loop/acrylic pad from palatal floor	4 mm		8 mm		12 mm	
Appliance	TPA	VHA	TPA	VHA	TPA	VHA
VAS scores	8	6	6	5	3	2
	7	5	5	6	2	2
	5	6	6	5	3	3
	7	7	6	5	4	1
	6	7	7	6	4	2
Mean score	**6.6**	**6.2**	**6**	**5.4**	**3.2**	**2.0**

point of application of force.[20,21] This might explains the lower values of stress that we obtained at the three apices of the molars in all six models. The furcation area being intermittently distant from the point of application of force has stresses lower than the cervical area but higher than the apex. The root curvature in the area of the apex is another factor that could have contributed to a significant difference in stress between the furcation area and the three apices.

Based on the results of the present study, it is evident that the VHA models can generate substantially higher von Mises stresses as compared to the corresponding TPA models at all three different heights of the loop/acrylic pad. This could be explained by the fact that the VHA has a more complicated geometry compared to TPA, incorporating helices and loops in the structure. This increases the overall stiffness of the VHA and hence an increase in the value of stresses would result, which is also validated and explained by DeBerardinis et al., 2000 in the American Journal of Orthodontics.[1]

Lee proposed a stress range of between 150 g/cm^2 and 260 g/cm^2 (equivalent to between 14700.97 Pa and 25497.26 Pa).[22,23] Bench proposed 100 g/cm^2 (equivalent to 9800.65 Pa) as the appropriate stress in the PDL for tooth movement as it would preserve the vascularity with a minimum of hyalinization.[22,24] The stress values from this study at various areas of the PDL complied with the aforementioned values given by Lee and Bench.[22–24]

Based on the results obtained, it is evident that the stress values show a significant increase in most of the areas as we changed the height of the acrylic pad of the VHA from 4 mm to 8 mm. This is suggestive of the better effectiveness of the VHA in terms of its objective of restricting extrusion or somewhat intruding on the molars. However, when we increased the height of the acrylic pad of the VHA further from 8 mm to 12 mm, there seems to be a decrease in the stress values at all the areas except a marginal increase in the cervical area which might not have much clinical implication as the overall stress is still significantly lower. Thus, the 8 mm height of the acrylic pad of the VHA seems to be the most effective, followed by the 4 mm model. The 12 mm model generates stress values even lower than the 4 mm model for most of the areas, except for a marginal increase in the cervical area and the palatal root apex, which would not be sufficient to improve its function as the overall stress generated would still be significantly lower than the 4 mm model. The lowest overall stresses generated by the 12 mm model could be explained by a significant change in the geometry of the appliance. As the 12 mm model has a modified wire configuration, compressive bending stress may be experienced in the root which may have reduced the resultant von Mises stress. Among the TPA models, the 4 mm model generated much higher stresses compared to the 8 mm and 12 mm models, except for a marginal increase in the palatal root apex area which may not be enough to restrict the extrusion of the molars. The overall stresses generated in the VHA model were much higher than those in the TPA model, thus establishing the fact that the VHA is more effective in its functional ability compared to TPA. The 8 mm model of the VHA was found to be especially effective, providing higher yet within the physiologic limit of stresses.

The comfort of the patient, as determined from the VAS scores, demonstrated that the TPA at 4 mm was most comfortable for the patient, closely followed by the 4 mm VHA, 8 mm TPA and 8 mm VHA models. It is believed that vertical grower patients with a constricted maxillary arch and high palatal vault will have minimal discomfort even if the acrylic pad is at an 8 mm distance from the palatal mucosa. In this way, the VHA would generate considerably higher yet within the physiologic limit of stresses for restricting the extrusion of molars or somewhat intruding them, thereby enhancing the effectiveness of VHA, especially in vertical grower patients.

One of the limitations of this model is the uniform thickness (0.25 mm) of the PDL, that was considered to keep the model simple and yet render results very similar to the physiological responses of PDL. However, in reality, the PDL is hour-glass shaped, ranging in thickness between 0.15 mm and 0.38 mm, with its narrowest region in the furcation area in a multi-rooted tooth. The maximum thickness was observed at the cervical areas and apices.[25–27]

Conclusion

The VHA is more effective compared to TPA in terms of generating higher stresses and thus restricting the extrusion of the maxillary first molars. The 8 mm height of the acrylic pad of VHA generates particularly higher stresses as compared to other heights of loop/acrylic pad of TPA and VHA and hence would be more efficient functionally. Patient compliance with the 8 mm height of acrylic pad of VHA can be considered acceptable for most patients.

Source of funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors have no conflicts of interest to declare.

Ethical approval

Ethical approval was obtained from the ethical review board at Siksha O Anusandhan University (reference no. DMR/IMS.SH/SOA/180151) date of approval was 25th January 2019.

Authors contributions

TKN and SP conceptualised this study. AS and RP were responsible for the study and data acquisition. TKN, SP, and SBN supervised the study, and SNS helped in data acquisition. AS and SP drafted the manuscript and were finalised by TKN and SBN. AS and TKN are responsible for all aspects of the work in ensuring that the questions are related. All authors have critically reviewed and approved the final draft and are responsible for the content and similarity index of the manuscript.

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How to cite this article: Nayak TK, Nanda SB, Sinha A, Pradhan R, Pattanaik S, Sahoo SN. Comparative evaluation of transpalatal arch and vertical holding appliance at different heights. J Taibah Univ Med Sc 2022;17(3):401–407.