Original Article

Asymmetric Outer Bow Length and Cervical Headgear Force System: 3D Analysis Using Finite Element Method

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Abstract

Objectives: This study sought to assess distal and lateral forces and moments of asymmetric headgears by variable outer bow lengths.

Materials and Methods: Four 3D finite element method (FEM) models of a cervical headgear attached to the maxillary first molars were designed in SolidWorks 2010 software and transferred to ANSYS Workbench ver. 11 software. Models contained the first molars, their periodontal ligament (PDL), cancellous and cortical bones, a mesiodistal slice of the maxillae and the headgear. Models were the same except for the outer bow length in headgears. The headgear was symmetric in model 1. In models 2 to 4, the headgears were asymmetric in length with differences of 5mm, 10mm and 15mm, respectively. A 2.5 N force in horizontal plane was applied and the loading manner of each side of the outer bow was calculated trigonometrically using data from a volunteer.

Results: The 15mm difference in outer bow length caused the greatest difference in lateral (=0.21 N) and distal (= 1.008 N) forces and also generated moments (5.044 N.mm).

Conclusion: As the difference in outer bow length became greater, asymmetric effects increased. Greater distal force in the longer arm side was associated with greater lateral force towards the shorter arm side and more net yawing moment.

Clinical Relevance:

A difference range of 1mm to 15 mm of length in cervical headgear can be considered as a safe length of outer bow shortening in clinical use.

Keywords: Orthodontic; Extraoral Traction Appliances; Force; Unilateral; Finite Element Analysis

Journal of Dentistry, Tehran University of Medical Sciences, Tehran, Iran (2015; Vol. 12, No. 3)

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Received: 14 August 2014
Accepted: 28 December 2014

INTRODUCTION

A shift to non-extraction orthodontic treatment seems to be occurring in contemporary orthodontics [1]. Therefore, space regaining treatment modalities are highly important in order to alleviate crowding and establish an ideal occlusion. Molar distalization is one method for space regaining, for example, in unilateral class II malocclusions. This type of malocclusion is often a challenge for practitioners [2]. Treatment modalities for this malocclusion include: asymmetric headgear (AHG), asym-

metric extractions, differential elastic patterns, intraoral anchorage appliances, and, more recently, temporary skeletal anchorage devices (TADs)[3-6]. Extensive clinical data have demonstrated the effectiveness of AHG in unilateral distalization [2].

Traction with headgears has some important advantages such as maximum anchorage to adjust the force and control of bodily or tipping movement [7].Unlike most of the other fixed appliances for molar distalization, headgear does not lead to protrusion of anchorage teeth[8]. Different modifications of AHG have been designed and evaluated, such as anterior swivel joint for the connection between inner and outer bows, an internal hinge on the inner bow, and use of long and short outer bows [9]. Undoubtedly, AHG applies an unequal distal force; but it should be noticed that the common side effect in all designs is the lateral force produced.

Although many theoretical and experimental studies were performed to evaluate the effect and side effects of AHGs, the results were confusing. Nobel and Waters [10] showed that AHG produced a buccal displacement in the transverse dimension as a side effect. On the other hand, Hershey and his colleagues [11] found some buccal-buccal displacement and some lingual-buccal displacement of the molars; the buccal-buccal displacement was attributed to the arch expansion effect of the inner bow. Martina [12] and Yashida[9] stated that AHG often produced buccal cross bite in the light force side and lingual cross bite in the heavy force side; however, they believed that the magnitudes were not equal on both sides.

Geramy analyzed the cervical headgear force system using finite element method and reported the same distalizing force in both side molars when all dimensions were considered ideal [13]. In some instances, asymmetries may arise inadvertently. Geramy et al. analyzed the force system in detail when a modification in molar situation or inner bow form resulted in different distalizing forces and an asymmetric headgear was produced [14]. FEM, as a numerical analysis to find approximate solution to complex problems, was first introduced in aerospace industry and soon entered into different fields of biology. Its efficacy in different fields of science has been well proven. Three-dimensional FEM is a powerful discipline used to examine complex mechanical behaviors of dental structures. It can be used for designing, analysis and finding answers to dental biomechanical problems [15-20].

MATERIALS AND METHODS

Five 3D finite element models of a mesiodistal slice of the maxillae were designed. The models contained upper first molars, their PDLs, cancellous bone, cortical bone, stainless steel molar bands fitted to molar crowns, and a cervical headgear. The difference in models was in the outer bow length in the cervical headgear, which was symmetric in the first model and asymmetric in models 2 to 4. The length difference (shortening of the left outer bow) was 5 mm (model 2), 10 mm (model 3), and 15 mm (model 4). Wire diameter was 1.6 mm in the outer bow and 0.9 mm in the inner bow (Figure 1). The last model was the same as the fourth one except for the molar teeth, which were replaced by two blocks. This replacement was done to simplify viewing the details of displacements occurred in headgear loading and to make an unforgettable image of the molar reaction (in the fourth model).

The models were designed in SolidWorks 2010 (SolidWorks Corp., MA, USA) and were then transferred to ANSYS Workbench ver. 11 (ANSYS, PA,USA) for the solving process. To find the angles formed between the outer bow and its tangent to the neck, accurate trigonometric calculations were made using SolidWorks. Distances needed to draw Figure 2 were derived from a volunteer dental student by a clinical vernier caliper. In this way, the exact force components in the anteroposterior and mediolateral directions were found.

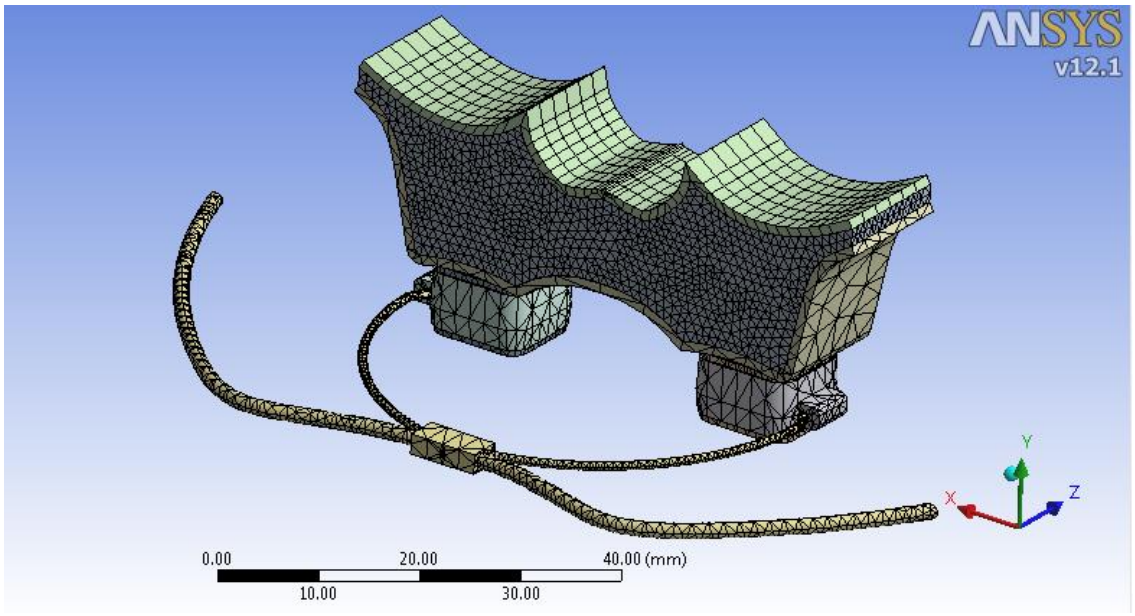

Fig 1. The 3D model of a slice of the maxillae containing the first molars, their PDLs, upper molar bands, spongy and cortical bones, and a cervical headgear with unequal outer bow lengths (the left outer bow is shortened)

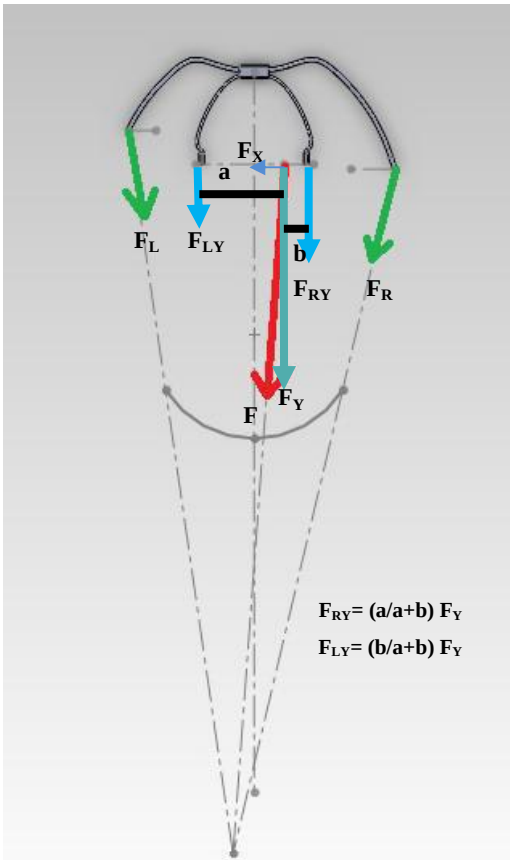

Fig 2. The force system of a cervical headgear with unequal outer bow lengths (the distances were measured in a volunteer using a caliper in the clinic)

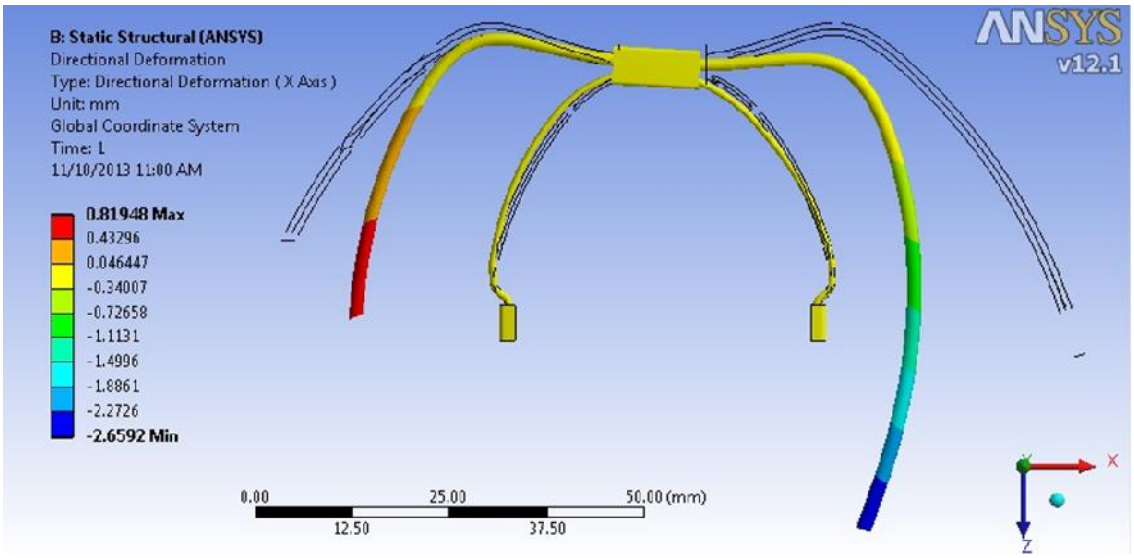

Fig 3a. Outer bow displacement (X5) to show the manner of deformation under loading.

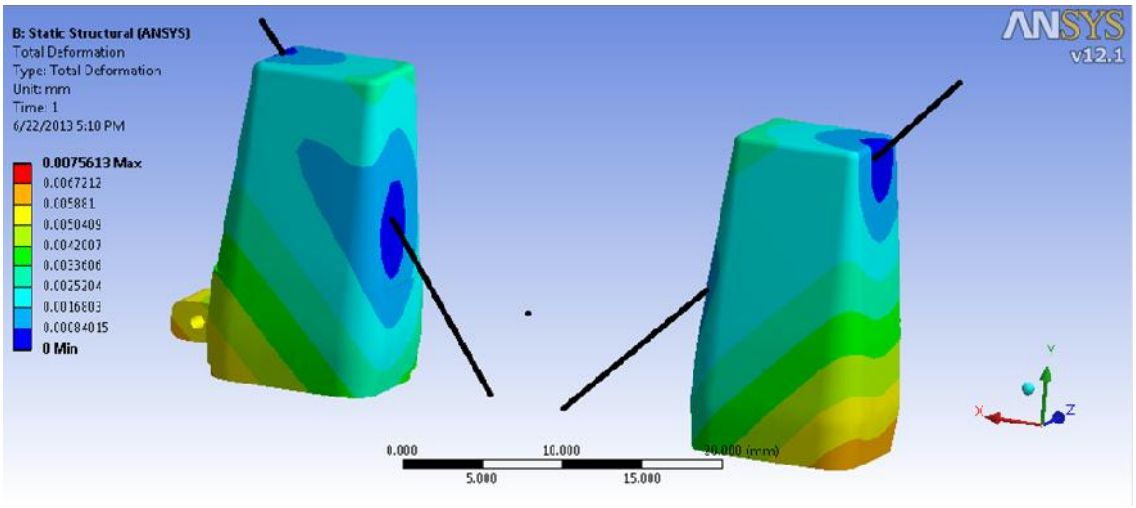

Fig 3b. Replacing the teeth with two blocks made it easier to show the displacements. The black lines represent the rotation axes (the right band is kept).

The force components were uploaded into ANSYS Workbench to conduct a static analysis. The outer bow bending under loading was analyzed.

Headgear was considered to be made of stainless steel (Young's modulus = 200000 MPa; Poisson's ratio= 0.3). Meshing was done by the meshing program in the ANSYS Workbench. Meshed models contained 141,777 nodes and 82,023 elements (Figure 2). Materials used in models were defined (Table 1).

Outer bow ends were loaded with 2.5 N force in horizontal plane decomposed in mediolateral and anteroposterior directions. The distalizing and laterally directed force to molars and moments were evaluated.

RESULTS

A deformation was noticed in the headgear when connected to the neck pad. Outer bow deformations were not symmetric and are shown in Figure 3a.

This deformation produced a complex movement, which provided a new insight of the displacement events that occur in headgear users (Figure 3b).

Lateral force

Buccal movement was observed on the short bow side, and lingual displacement on the intact bow side.

Table 1. The mechanical properties of the materials used in the models

	Young's modulus	Poisson's ratio
Cortical Bone	34000	0.26
Spongy bone	13400	0.38
PDL	0.667	0.49
Tooth	20300	0.26
Stainless steel	200000	0.3

Table 2. The lateral force findings (N)

	Intact side molar	Shortened arm side	Force diff.
Symmetric HG	1.2089	1.2089	0
5 mm	1.2494	1.1778	0.0716
10 mm	1.2862	1.1474	0.1388
15 mm	1.3292	1.1154	0.2138

Table 3. The distal force findings (N)

	Intact side molar	Shortened arm side	Force diff.
Symmetric HG	2.4339	2.4339	0
5 mm	2.5973	2.2845	0.3128
10 mm	2.769	2.1266	0.6424
15 mm	2.9578	1.9498	1.008

Table 4. The moment findings (N.mm)

	Intact side molar	Shortened arm side	Moment difference
Symmetric HG	-15.41*	15.393	-0.017
5 mm	-16.274	14.629	-1.645
10 mm	-17.129	13.857	-3.272
15 mm	-18.08	13.036	-5.044

* (Negative moments tend to rotate the system in a clockwise direction when viewed apicoocclusally)

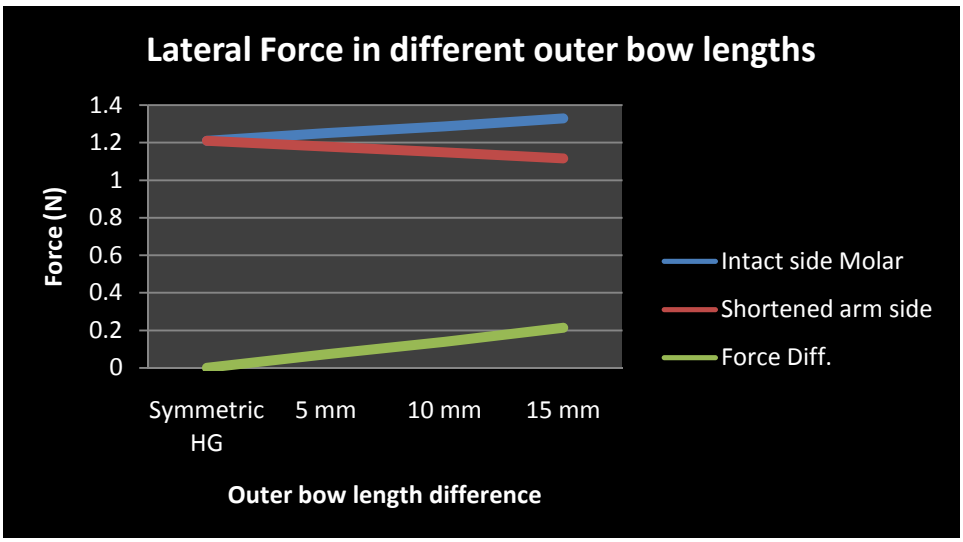

Fig 4. The influence of asymmetric outer bow on lateral force

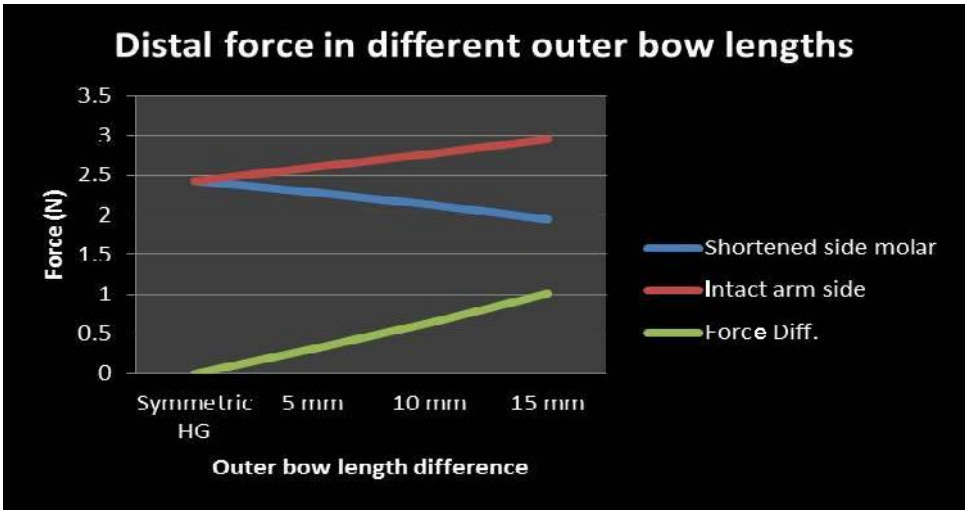

Fig 5. The influence of asymmetric outer bow on distal force

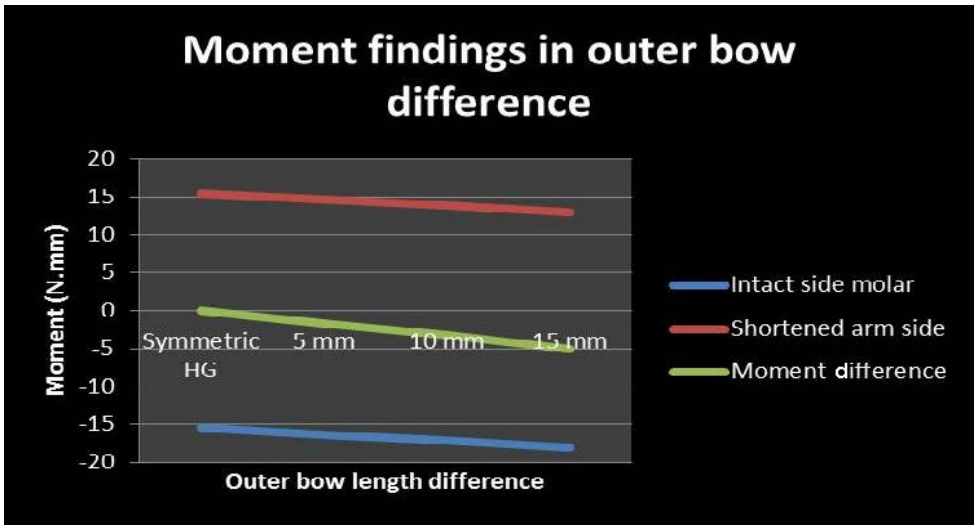

Fig 6. The influence of asymmetric outer bow on moment

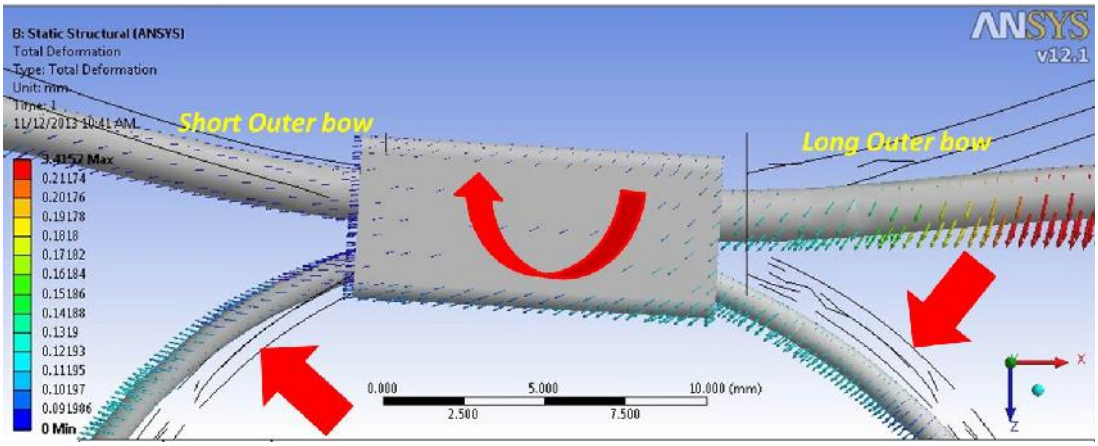

Fig 7a. A closer view of Figure 3a showing the effect of a clockwise moment on the outer bow/inner bow junction. Note the manner of inner bow deformation representing the system yaw. The structure before deformation is shown in thin black lines.

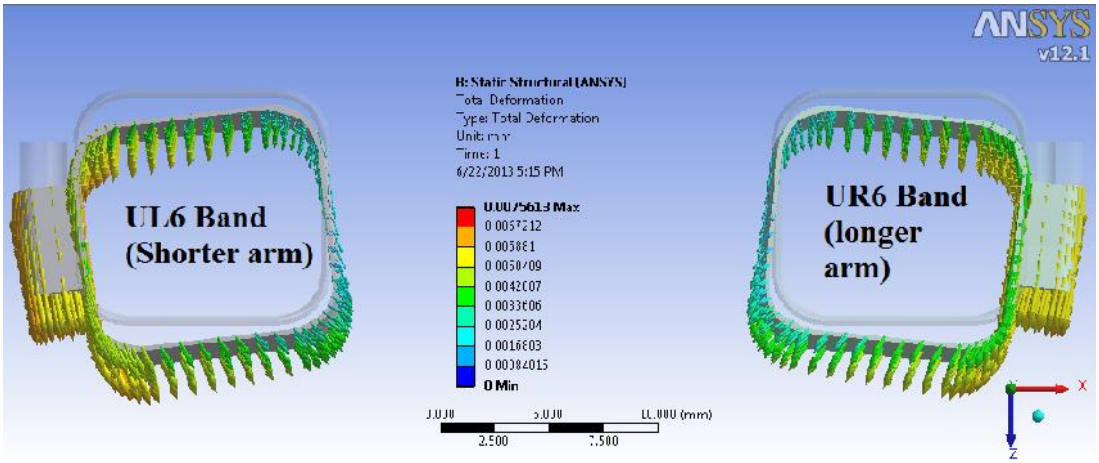

Fig 7b. An apico-occlusal view of distal movement of the bands (teeth), a rotation caused by the off center force application (the distance between the buccal tube and the tooth long axis), and a clockwise yawing moment; although not easily noticeable (UL6 = upper left first molar; UR6= upper right first molar).

The results showed that the greater the magnitude of difference in outer bow length, the greater the asymmetric effect produced by the headgear (Figure 4). In other words, by increasing the difference in length of the outer bow, lateral force decreased in short bow; but in the intact bow, we observed an incremental increase in the magnitude.

Among the three situations of the headgear, the greatest asymmetric effect was observed when difference in length was 15 mm, followed by 10 mm, and 5 mm.

Table 2 shows the lateral force and the effect produced by the application of each asymmetric headgear. The lateral effect was acquired by subtracting the lateral force produced in the intact bow from that in the short outer bow. This value showed the tendency to move molars in a transverse direction (intact bow-short bow direction).

Distal force

Distal force had the same trend as the lateral force. But, It should be noticed that force dif-

ferences were greater for distal forces than for lateral forces in the same length differences. It means that greater asymmetric effect was ob served due to distal than lateral force. Table 3 shows distal force and the effect produced by each asymmetric headgear (Figure 5).

Moment

Moment differences showed the same behavior. As the outer bow length decreased, moment difference increased; in symmetric condition, difference was small and negligible, and no difference was considered.

In 5 mm length, the difference was 1.645 N.mm and was then increased to 5.044 N.mm in 15 mm. It should be noticed that the net moment and the intact bow moment had the same direction. Figure 6 shows the effect of asymmetric outer bow on the moments and the net moment.

DISCUSSION

In 1958, Haack and Weinstein [21] proposed a static analysis for orthodontic headgear, assuming that lateral forces applied to the two molars must be equal in magnitude and direction. In an asymmetric headgear, the resultant force from the right and left tractive forces intersects and divides the inter-molar line into unequal distances of a and b (Figure 2). The distal force is distributed to the right and left molars in proportion to the ratio of a and b.

In our study, the results showed that among the 3 models of asymmetric headgear, the greatest distal effect was observed when length difference was 15 mm. This finding is in accordance with the results of Haack and Weinstein [1], Oosthuizen[22] and Baladini [23]. In other words, increases in length difference boosts the asymmetric effect.

According to the results of the current study, lateral force displaced the molar towards buccal from intact bow side to short bow side. In other words, lateral force results in buccal cross bite in the short bow side and lingual cross bite in the intact bow side.

According to Haack and Wienstein [21], laterally directed force is an inevitable component of asymmetric headgears. They believed that the net lateral force was directed toward light force side from the heavy force side, and the ratio was 1:1. However, other studies including ours are against this theory. In our study, lateral force was unequal and it was greater in the intact bow side than the short bow side. Also, this force increased as the asymmetry increased. Yoshida [9] believes that the proportion of laterally directed forces between the two sides is not 1:1 and this proportion depends on Young's modulus and the second moment of area. Yashida [9] and Martina [12] stated that this lateral displacement had a buccal direction from heavy to light force side. On the other hand, Hershey [24], Nobel[10] and Breier [25] showed that displacement of both molars was towards the buccal in transverse direction. Furthermore, Noble [10] stated that lateral force was lower in the heavy force side than in the light force side. Yoshida [9] confirmed this finding by examining on human data. Results about this issue seem to be controversial. Yoshida attributed this controversy to discrepancy in configuration of headgears tested. Nobel [10] showed that the lateral force had a fluctuating behavior. It means that the buccal force in the heavy force side decreased by increasing asymmetry in a small range; but out of this range, buccal force decreased and finally it turned into a lingually directed force. This seems to be related to the inner bow wire diameter. Decreasing the inner bow diameter will result in a laterally directed force produced by inner bow buckling. This force will decrease the lingual cross bite tendency in the long outer bow side and increase this tendency in the short outer bow side.

Buccal displacement in the short bow side seems to have negligible clinical side effects, because it maintains the buccal overjet in the light side [9]. On the contrary, lingual cross bite in the intact bow side is an inevitable disadvantage.

Evaluation of the moment produced by the asymmetric headgear showed that distal rotation was greater in intact bow side than in the short side.

The moment difference and the degree of asymmetry had a direct relation. However, Yoshida [9] and Noble [10] showed that distal rotation was greater in the shorter bow. Figures 7a and 7b provide unique views of how the net moment affects the system. The yawing effect is clearly shown (from an apicoocclusal view) in Figure 7a.

Adding all effects, upper molars are distalized under the distalizing component of the applied force, which is the main goal of using this asymmetric headgear. There is also a tendency to displace these teeth laterally (toward the shorter outer bow), which is not favorable. A less noticed effect is rotation around the vertical axis, which makes it difficult to summarize all treatment effects for the purpose of explanation or instruction.

CONCLUSION

Shortening the outer bow of a cervical headgear makes an appliance that produces unequal distalizing force, which results in favorable therapeutic effects, a lateral driving force which is an undesirable side effect directing from the long arm side towards the short arm side and thus inducing a tendency for palatal cross bite in the long arm side molar and a buccal cross bite in the short arm side molar, and a net yaw moment to rotate the system (the whole dental arch or the terminal molars depending on the system design) in a clockwise or counterclockwise direction, which complicates the interpretation of displacements. This system seems to have hidden points, not covered in orthodontic textbooks.

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