Original Article

Optimization of Unilateral Overjet Management: Three-Dimensional Analysis by the Finite Element Method

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Abstract: The main goal of this research was to introduce, evaluate, and mathematically optimize the treatment procedure of unilateral overjet cases. Patients with Class II subdivision malocclusions usually reach a point with canines in a Class I position, and a unilateral overjet remains to be treated at the next stage of treatment. This study tried to prepare an archwire design that combines the midline-shift correction and the unilateral overjet reduction simultaneously. The analyses of displacements were carried out by the finite element method. The upper dental arch was designed three-dimensionally. Three archwire designs that were thought to be useful in these cases were modeled and engaged the dental-arch model separately. Three-dimensional displacements of the mesio- and distoincisolabial point angles of each incisor were assessed. Shortcomings of each design concerning the main treatment objectives were eliminated by optimization. Modeling and optimization of wire ligation methods were the last phase of this study. The use of an archwire containing a closed vertical loop with a helix distal to the lateral incisor on the affected (excess overjet) side and an open vertical loop without a helix distal to the lateral incisor on the normal side (normal overjet) while lacing the four incisors can be suggested as an optimum procedure to treat a unilateral overjet that is combined with a midline shift. The archwire cross-section depends on the initial position of the incisors. This mechanotherapy can be prescribed for both dental arches. (*Angle Orthod* 2002;72:585–592.)

Key Words: Class II; Subdivision treatment; Midline correction; Asymmetric overjet; Finite element method

INTRODUCTION

Despite the efforts of many authors and researchers to explain the nature of tooth movement in continuous arch techniques[1–6] and mechanics,[7–11] much work remains to be done to make the different views in this field of research clear. Burstone and Koenig[10] explained the manner of tooth movement in relation to bracket angulations on the adjacent teeth. The classification presented was clear and was applicable to predict the resultant movements. The force systems produced by different V-bend positions and the step bend and the resultant movements produced at the adjacent teeth were the main aspects of the research conducted by Burstone and Koenig,[11] in which some clinical points of continuous arch mechanics were explained. Mulligan,[12,13] in a series of articles, defined simple rules to explain the mechanical principles of continuous arch techniques.

Researchers, however, have not discussed overjet reduction by continuous arch techniques as an important phase of treatment. The classic method is to correct the midline and produce equal spaces distal to both lateral incisors (upper or lower ones) and to retract them at the next stage. Unilateral overjet management is the next phase of the treatment of a Class II subdivision patient after removal of the first premolar tooth at the Class II side. Of course, the condition will be reverse for an asymmetric overjet combined with a lower midline shift produced by an asymmetric position of the lower canines. In this situation, a Class III (affected side) canine relationship will be accompanied by a Class I (normal side) relation. Canine retraction after removal of the affected-side premolar will produce such a condition for the lower incisors. This procedure takes more than the usual time because of the presence of midline shift and the asymmetric nature of the overjet (normal overjet at the Class I side, but excessive on the subdivision side). Using an archwire, which corrects midline shift and unilateral (asymmetric) overjet simultaneously, can reduce the duration of this phase. It is the first time that a three-dimensional (3D) finite element model has been designed to evaluate such a treatment procedure.

New designs or modifications of classic methods should be evaluated for unwanted or harmful side effects before their application in the clinic. Finite element method (FEM)

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is the most reliable method for providing a clear understanding of the occurrences in an unknown process. This method is by far the best one to provide the researcher with simulations as real as possible. One of the most important advantages of this method, which cannot be found in any in vitro experiment, is that it provides the ability to optimize a process numerically and accurately. Application of a new archwire design without considering its complete functions is not in accordance with medical ethics. In addition, it is not possible to evaluate the treatment effects of a new archwire design in the mouth so accurately. Therefore, FEM was selected to accomplish the calculation of displacements. This method has proven its efficiency in different applications in orthodontics.[14–21]

This study tried to optimize this procedure through improving the arch designs step by step to reach treatment goals and eliminate or minimize the unwanted side effects.

MATERIALS AND METHODS

The FEM, a numerical way to find stress, displacement, and strain, was selected for the calculations. Sap90 Version 5.20 (Computers and Structures Inc, Berkeley, Calif) was the software with which the model was constructed and the analyses performed. On the basis of the similarities between the upper and lower dental arch mechanotherapies used to treat an asymmetric overjet or reverse overjet, the upper dental arch was selected to be modeled by the author. It contained four incisors, with details of shape and size taken from Ash[22] with little modification. Representations of seven posterior teeth were modeled with the minimum of nodes, considering the extraction of the premolar on the affected side. Combining different mesh sizes in a 3D FEM can reduce the node numbers when not necessary and maintain the accuracy when needed.[23,24] Modeling with different mesh sizes is an accepted way to reduce the problem size and the input file.[23,24] According to the goals of this study, more attention is paid to the incisor teeth. The posterior teeth play a supporting role with their root surfaces as a determining factor.

The role of PDM as a linear elastic support is provided by the springs, which can be defined precisely from the nodes present at the root surface of the tooth models. In this way, the supporting structures were eliminated to make the problem solvable for the software.

To find out the spring rate of the PDM (modeled as a group of springs) of a normal tooth, a 1-N intruding force was applied to the labial side of a model with normal supporting structures (called Geramy 24),[18] and the amount of intrusion was measured. Multiple springs were defined according to the number of the nodes at the outer surface of the tooth roots to reach the value calculated.

A total number of 1654 nodes and 638 brick elements of eight-node were used to construct the dental arch as the first phase of modeling (Figure 1a). Each node's data consisted of 3D coordinates (X, mediolateral direction; Y, anteroposterior direction; and Z, supero-inferior direction) and their boundary conditions. The second phase consisted of preparing the archwire models. They were modeled as a series of two-node beam elements. Key points were defined at the critical locations such as canine and molar offsets, the start and the end of the anterior curvature, and different locations in the loop designs.

Sap90, like other FEM software, provides the designer with the ability to constrain different nodes at separate parts of a model. In this way, movement of a node in one part (the teeth, for example) of the model is followed exactly by the constrained node(s) at the other part (the archwire, for example) according to the manner of the defined constraints. It is limited by the degrees of freedom defined for a given element type. A close relationship between two nodes can be defined by constraining all the movements (for solid elements) and also rotations (for beam elements). The loops were 7 mm in height and 5 mm in width.

The wire engagement phase consisted of constraining proper nodes at the archwire with corresponding nodes at the labial surface of the teeth. The manner of constraining differed from one phase of the study to the other. Because the cross-section of the wire was considered to be round, there were no correlations of rotations between the archwire and the teeth. In other words, any moment potentially produced by torsion occurring at the archwire was not transferred to the teeth. All the supero-inferior and mediolateral movements of the posterior segment of the wire were constrained to the posterior teeth, and all the supero-inferior and anteroposterior movements of the anterior segment of the wire were constrained to the anterior teeth.

Table 1 shows the details of the tooth dimensions within the 3D model. The right-side occlusion was considered normal with the canines and the first molars in a Class I relation. A midline shift of the upper dental arch to the right and an asymmetric overjet increasing from the right to the left side of the arch were also modeled. A Class II molar relationship was considered at the left side of the dental arch. The left side, which had been corrected to a Class I canine relationship after removal of the upper-left first premolar, henceforth will be called the affected side and the other quadrant, the normal one. The true midline can be visualized to pass through the midpoint of the line connecting both canines with a right-angle direction. This line does not coincide with the position of the contact point of the incisors in the model.

The simplest archwire that seemed to meet the requirements of this treatment procedure was designed first. It contained a vertical, closed, helical loop with a helix on the affected side, distal to the lateral incisor; this design is hereupon called the ‘‘1L’’ design (Figure 1b). Although the archwire design can have either a round or a rectangular cross-section, all the archwires designed for this study (which will be discussed later) were considered to have a

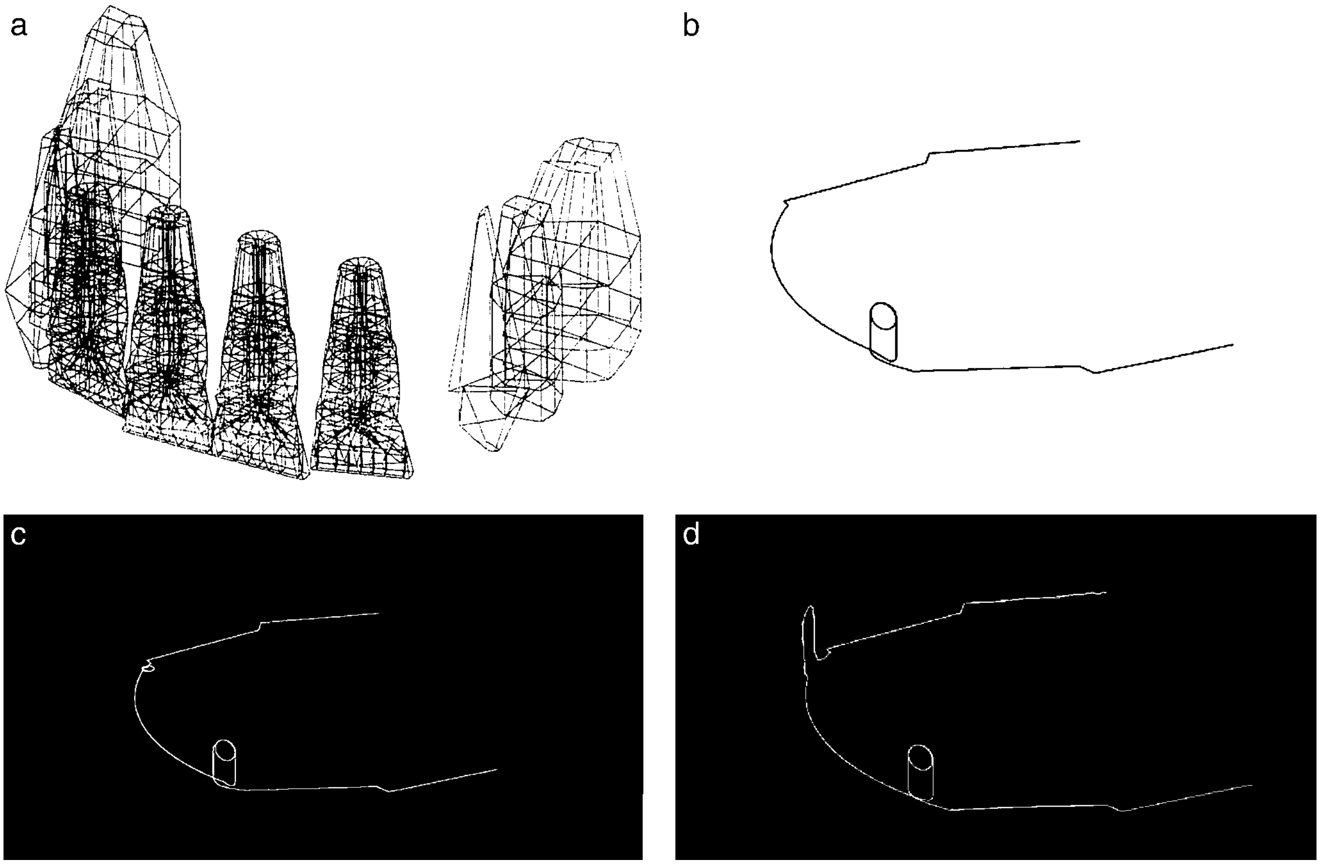

FIGURE 1. (a) 3D model of upper dental arch. (b) 3D model of the first archwire design with a closed helical loop. (c) 3D model of the archwire adding a helix at the normal-side lateral incisor. (d) 3D model of the archwire with two loops. A closed, vertical, helical loop at the affected side, distal to the lateral incisor, and an open vertical loop, distal to the normal-side lateral incisor.

TABLE 1. Dimensions of the Teeth Modeled

	Buccopalatal Dimension, (mm)	Mesiodistal Dimension, (mm)	Inciso-(occluso-) apical dimension, (mm)
Central incisor	7	8.5	21.5
Lateral incisor	6	6.15	19.5
Canine	7.5	7.5	22
First premolar	7	7	17
Second premolar	7	7	18
First molar	10.5	8	19

round cross-section with a diameter of 0.4 mm. The selection of the wire cross-section depends on the clinician's experience on the basis of the position of the root apex of the incisors at the start of this phase. This study did not consider the torque control and left the decision making to the clinician. Two hundred thirty-five beam elements of two nodes were used to make the archwire. The physical properties needed to define the archwire and the teeth are presented in Table 2. It should be mentioned that any tooth deformation has been ignored; the tooth material has been considered rigid.

TABLE 2. Mechanical Properties Needed to Define the Materials Involved

	Young's Modulus (MPa)	Poisson's Ratio
Orthodontic wire	2.10×10^5	0.3
Tooth material	2.03×10^4	0.26

Movements toward the left side, extrusive displacements, and retractions were considered to have negative signs. Other movements were considered to have positive signs.

In each phase of the study, an archwire design was prepared for the same dental arch. Displacements of the teeth were constrained by the movement of the archwire nodes when subjected to different activations at the first stage of the study. Nodes at the mesial and distal sides of incisal edges of upper incisors were selected for displacement assessment (mesio- and distolabioincisal point angles). At this phase of the study, the end of the archwire on the normal side was cinched (not being able to move). The other end of the archwire was displaced by 1 mm to the distal side of the buccal tube of the affected-side molar to apply the activation force.

A close examination of the results from the first archwire

TABLE 3. 3D Displacement Components of the Incisor Teeth with Various Archwire Designs

	Distolabioincisal Point Angle			Mesiolabioincisal Point Angle		
	X[a]	Y	Z	X	Y	Z
Normal side lateral incisor						
2 Loop archwire	−0.0266	0.0741	−0.0104	−0.0317	0.0567	0.0122
1 Loop archwire	−0.0037	−0.0007	−0.0111	−0.0031	0.0015	−0.0058
1 Loop + 1 helix	−0.0042	−0.0175	−0.0075	−0.0028	−0.0125	−0.0045
2 Loop, 2 activation	−0.1123	−0.1738	−0.1096	−0.0811	−0.065	−0.0105
Normal side central incisor						
2 Loop archwire	−0.05	0.0041	−0.014	−0.0501	−0.0017	0.0116
1 Loop archwire	−0.001	0.0002	−0.0016	−0.0011	0.0001	−0.0011
1 Loop + 1 helix	−0.0007	−0.0088	−0.0024	−0.0008	−0.0086	−0.0021
2 Loop, 2 activation	−0.0157	−0.0234	−0.0076	−0.0157	−0.0238	0.0002
Affected side central incisor						
2 Loop archwire	−0.0521	−0.0409	0.0101	−0.0523	−0.0327	−0.0171
1 Loop archwire	−0.0007	−0.0029	−0.0002	−0.0008	−0.0016	−0.001
1 Loop + 1 helix	−0.0015	−0.0128	−0.0011	−0.0016	−0.011	−0.0023
2 Loop, 2 activation	−0.0194	−0.039	0.0009	−0.0195	−0.0346	−0.0096
Affected side lateral incisor						
2 Loop archwire	0.1223	−0.3851	−0.0905	0.0675	−0.194	−0.0063
1 Loop archwire	0.2162	−0.3562	−0.139	0.1393	−0.0892	0.0307
1 Loop + 1 helix	0.2005	−0.3589	−0.1201	0.1301	−0.1147	0.03
2 Loop, 2 activation	0.1401	−0.3384	−0.0956	0.0883	−0.158	0.004

[a] X; mediolateral direction; Y, anteroposterior direction; Z, supero-inferior direction of displacement.

model revealed that the treatment objectives were not reached completely and, therefore, the design needed optimization. Two different designs with an additional manner of activation (two-loop, two-side activation) were compared with the first model. The first of these two designs, made up of 255 beam elements, contained a helix in the plane of the archwire between the lateral incisor and the canine on the normal side, hereupon called the ‘‘LH’’ design (Figure 1c). In the second design, the helix was replaced with an open vertical loop at the same position as the helix, with the other characteristics remaining the same, and this design is hereupon called the ‘‘2L’’ design (Figure 1d). Two-loop, two-side activation was a phase in which the 2L design was activated by a 1-mm displacement of the affected-side archwire end and by a 0.5-mm activation of the normal-side archwire end simultaneously, hereupon called the ‘‘2L, 2activ.’’ design. Numerical findings from the 2L design were promising (see Tables 3 and 4).

Modeling three different methods of ligation for the 2L design followed the archwire optimization process. Different ligation methods were defined by the various methods of constraints between the archwire nodes and the teeth nodes and are as follows:

- A common way of wire engagement using O-rings that allowed the wire to slide through the bracket slots. In this phase, each tooth responded separately, and the boundary condition was defined so that free sliding of the wire was permitted and there was no transfer of mediolateral movements of the wire to the teeth.
- Using ligature wire segments to fasten each tooth tightly. In this way, each tooth responded separately, and the wire was not allowed to slide through the bracket slots. In this phase, the incisor teeth were so constrained with the archwire that the whole 3D displacements of the wire were transferred to them (the boundary condition).
- All four upper incisors were laced together. In this way, all the incisors responded as a single unit, at the same time not allowing the wire to slide. At this phase, nodes of the adjacent teeth were also constrained to each other (the boundary condition). The wire itself could not slide because of the method of constraint defined between the wire and the teeth and a new constraint also was imposed upon the adjacent teeth.

This archwire does not show any plastic deformation with clinical use after one visit; therefore, the analysis is restricted to the linear elastic phase of the materials.

RESULTS

All the results were divided into two main parts. The first part consisted of the evaluation of different arch designs, and the second part consisted of the evaluation of various forms of ligation in the selected archwire design. Each part contained 3D displacements and will be explained separately.

Part one

Anteroposterior displacement. The results revealed that the affected-side lateral and central incisors underwent the greatest movement toward correction (retraction) with the

TABLE 4. 3D Displacement of Components of the Upper Anterior Teeth with Various Ligation Methods

	Distal			Mesial		
	X[a]	Y	Z	X	Y	Z
Normal side lateral incisor						
2 Loop archwire	−0.0266	0.0742	−0.0104	−0.0317	0.0567	0.0122
Laced anterior teeth	−0.0135	0.0106	−0.0086	−0.0199	−0.01173	−0.0039
Loosed ligature	−0.1781	0.2363	−0.0892	−0.178	0.2367	0.0639
Normal side central incisor						
2 Loop archwire	−0.05	0.0041	−0.014	−0.0501	−0.0017	0.0166
Laced anterior teeth	−0.0199	−0.0117	−0.0039	−0.0193	−0.0394	−0.0014
Loosed ligature	0.0048	−0.1707	−0.0134	0.0048	−0.1708	−0.0178
Affected side central incisor						
2 Loop archwire	−0.0522	−0.0409	0.0101	−0.0523	−0.0327	−0.0171
Laced anterior teeth	−0.012	−0.0834	−0.014	−0.0194	−0.0394	−0.0014
Loosed ligature	−0.005	0.2711	0.026	−0.005	0.2711	0.0248
Affected side lateral incisor						
2 Loop archwire	0.1223	−0.3851	−0.0905	0.0675	−0.194	−0.0063
Laced anterior teeth	0.0419	−0.2503	−0.0518	−0.012	−0.0834	−0.014
Loosed ligature	0.3124	−0.5456	−0.1387	0.311	−0.5404	−0.0068

[a] X; mediolateral direction; Y, anteroposterior direction; Z, supero-inferior direction of displacement.

2L design. The amount of retraction decreases toward the normal-side central incisor. The normal-side lateral incisor underwent retraction with 2L, 2activ. and the LH designs, remained almost at the same place with the ‘‘L’’ design, and protracted with the 2L design. The L design cannot displace (retract) incisors except for the affected-side lateral incisor (Figure 2a).

Mediolateral displacements. All the findings of this part were promising except for the affected-side lateral incisor that showed an unwanted displacement (rotation). The mediolateral displacement for the 2L, 2activ. design decreased from the normal-side lateral incisor to the affected-side lateral incisor. This pattern was almost reversed for the 2L design, although with a less amount of displacement (Figure 2b).

Supero-inferior displacement. These findings showed changes in angulations with the 2L design (a negative finding on the distal and a positive one on the mesial side) for the normal-side lateral and central incisors and the affected-side central incisor. These three teeth underwent extrusion with the 1L, the LH, and the 2L, 2activ. designs. The affected-side lateral incisor underwent extrusion with the 2L design, and its apex tended to move away from the midline because of the changes in angulation with other designs (intrusion of the mesial and extrusion of the distal point angles). The highest amount of change in the angulation was produced by the 1L design (Figure 2c).

Part two

Anteroposterior displacement. Laced anterior teeth showed an increase in the amount of retraction from the normal-side lateral incisor toward the affected-side lateral incisor. Other ligation methods showed protraction and retraction of incisors (Figure 3a).

Mediolateral displacement. All the ligation methods produced favorable displacements toward the midline correction except for the affected-side lateral incisor. It was found that laced anterior teeth showed the best results with a minimum of unwanted displacements at the distal point angle of the affected-side lateral incisor, compared with the other ligation methods (Figure 3b).

Supero-inferior displacement. The only way to prevent any change in the angulations was to lace all the incisors. In this way, a mild extrusive displacement occurred in all the incisors (Figure 3c). There were changes in angulations with O-ring use for the incisors except for the affected-side lateral incisor, which underwent an extrusive displacement. Ligation of each tooth separately produced a change of angulation of the normal-side lateral incisor, extrusion for the normal-side central incisor and the affected-side lateral incisor, and an intrusive displacement for the affected-side central incisor (Figure 3c).

DISCUSSION

3D tooth models used in this study contained 11 solid blocks that responded separately. Defining springs to simulate the PDM helped to reduce the nodes needed. The incisors had shown their reliability through recent studies.[17,18] In this study, the manner of teeth response is far more important than the exact amount of displacement.

Optimization of a treatment process requires complete knowledge of the procedure, its shortcomings, and a clear image of what should occur. An optimized procedure in the

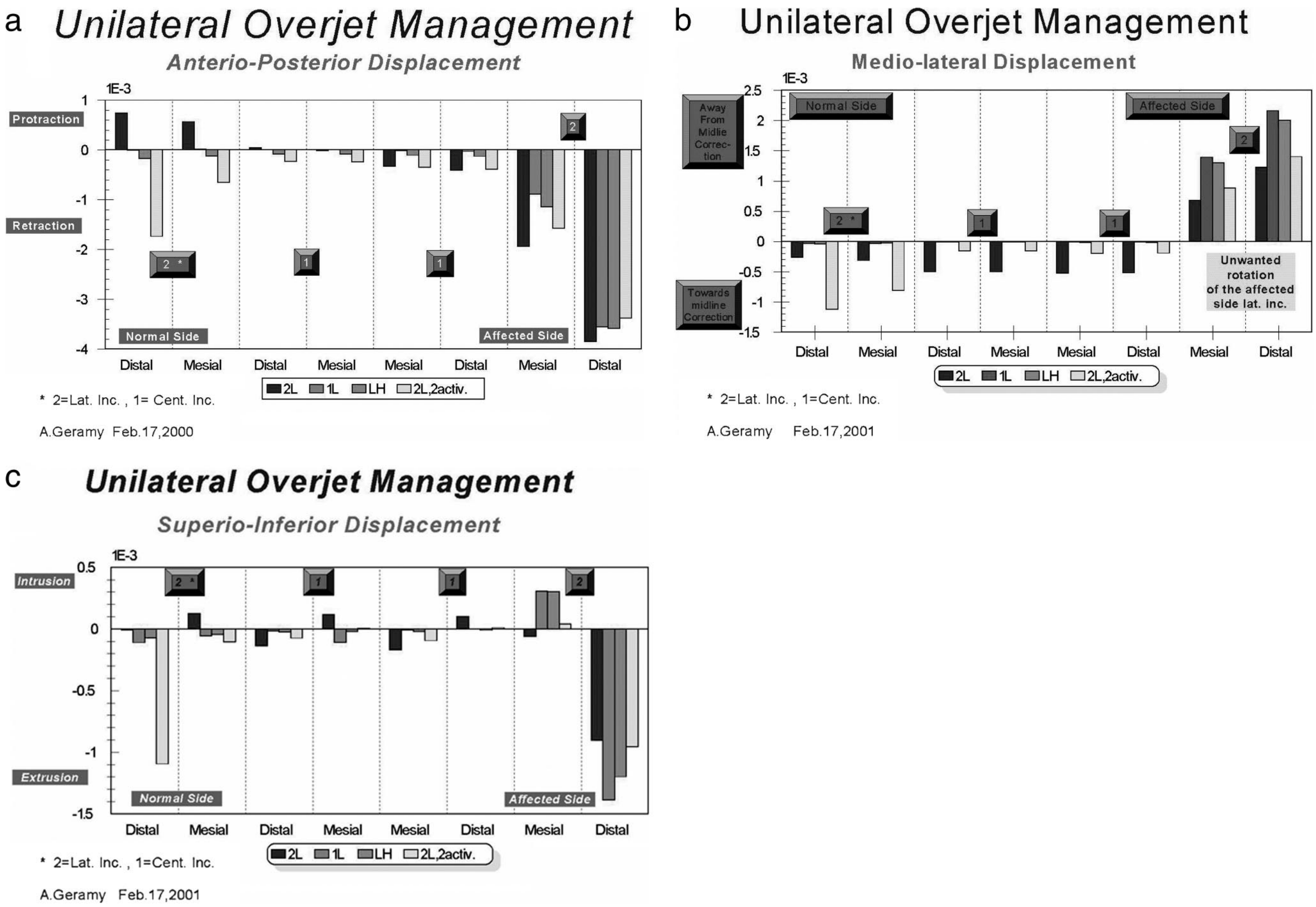

FIGURE 2. (a) Anteroposterior displacement of four incisors with different archwire designs. (b) Mediolateral displacement of the incisors with different archwire designs. (c) Supero-inferior displacement of four incisors with different archwire designs.

treatment of these cases seems to be optimum when it provides the practitioner with the following objectives:

- Increases in the anteroposterior movements of the upper incisors from the normal-side lateral incisor to the affected-side lateral incisor are expected. Occurrence of minimal anteroposterior displacement at the normal-side lateral incisor is desirable.
- The least amount of mediolateral displacement toward the midline correction is expected to occur at the normal-side lateral incisor and the greatest amount of displacement at the affected side. Occurrence of any displacement of this kind at the normal-side lateral incisor opens a space between the lateral incisor and the canine of the normal side.
- Lack of any supero-inferior displacement ensures the stability of the occlusal plane and the prevention of bite-depth alteration.

A close examination of the results presented in Figures 2a through c shows the nature of tooth responses with different archwire designs and their inadequacies to meet the aforementioned criteria. Some points worth mentioning are as follows:

- The L and LH designs did not displace the teeth anteroposteriorly except for the affected-side lateral incisor (Figure 2a).
- The 2L design showed a gradual change of displacements from the normal-side lateral incisor to the affected-side lateral incisor (Figure 2a).
- Protrusive movement of the normal-side lateral incisor (positive sign of movement in Figure 2a) was an unfavorable displacement and was hoped to be modified through the optimization process (Figure 2a).
- Any kind of rotation of the lateral incisors on both sides of the dental arch should be eliminated. This movement is evidenced by the different amount of negative and positive findings in the mesial and the distal point angles in Figure 2b. The affected-side lateral incisor experienced a distopalatal rotation with all the designs, and the most severe rotation is induced by the 1L design; however, the normal-side lateral incisor experienced this movement with the 2L, 2activ. method.
- A cursory examination of Figure 2c reveals that all the designs caused undesirable vertical movements at the incisors: change of the angulation or extrusion.

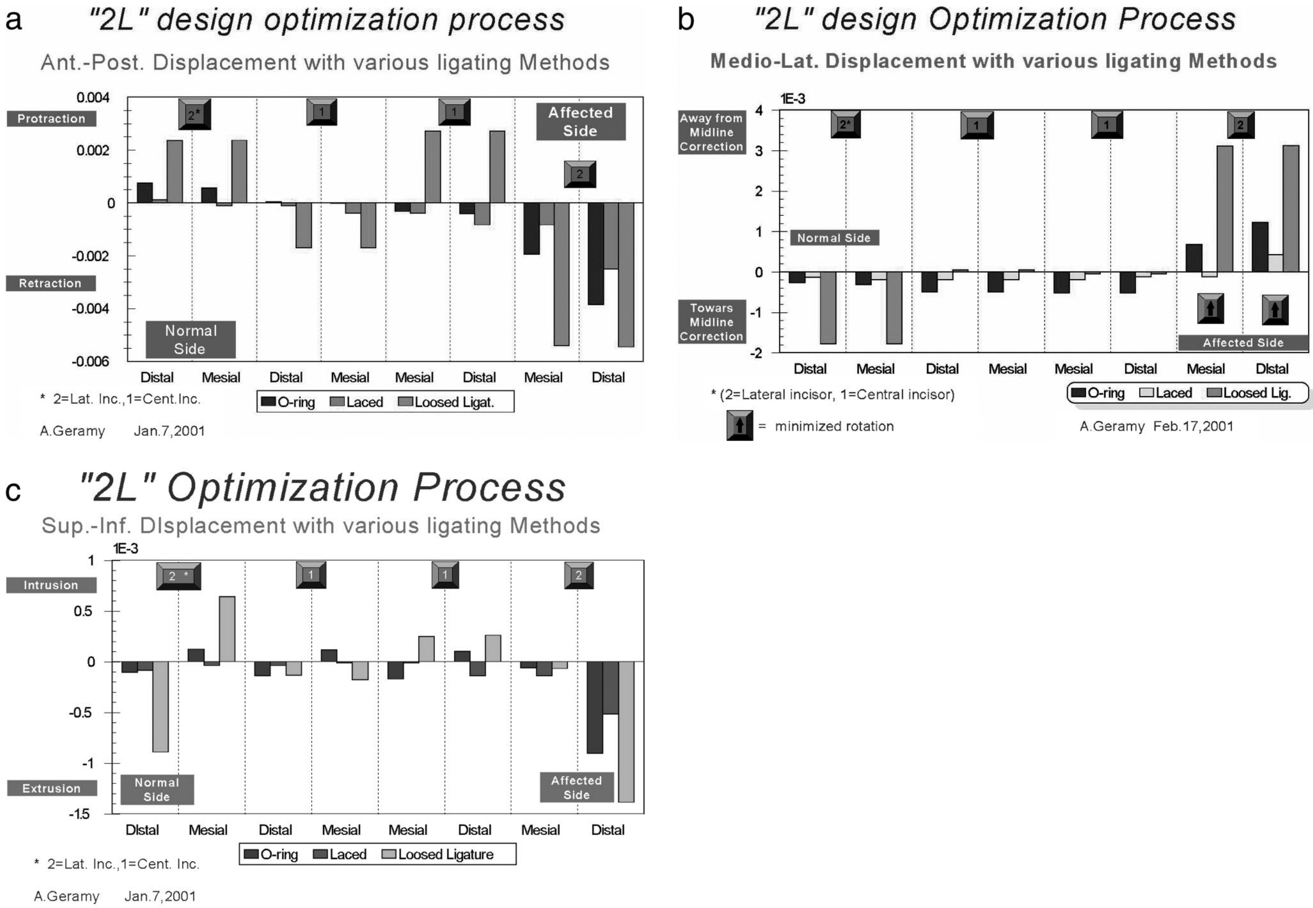

FIGURE 3. (a) Comparison of anteroposterior displacement of different ligation methods (the archwire with two loops). (b) Comparison of mediolateral displacement of different ligation methods (the archwire with two loops). (c) Comparison of supero-inferior displacement of different ligation methods (the archwire with two loops).

The optimization process continued with three main goals to be achieved:

1. Improvement of anteroposterior displacements of lateral incisors.
2. Maintenance of the vertical position of all the incisors.
3. Prevention of any rotation in lateral incisors.

Examination of Figures 3a through c revealed that the laced incisors did show the improvements expected. A gradual increase in the retraction of the incisors, increasing from the normal-side lateral incisor to the affected-side incisor with a negligible amount of protrusion at the distal point angle of the normal-side lateral incisor, is obvious (the least amount between other ligation methods) (Figure 3a).

A favorable displacement of all the incisors except for the affected-side lateral incisor toward the midline is produced, and the distopalatal rotation of the affected-side lateral incisor is minimized (Figure 3b).

An acceptable control of the vertical position of the incisors is established with the minimum amount of extrusion at the affected-side lateral incisor (Figure 3c).

The same design can be prescribed for the lower dental arch to correct the midline and the asymmetric reverse overjet produced by an asymmetric protraction of the lower incisors. Rectangular wires, when needed, can also be used. These archwires are used in the daily practice by the author.

The only limitation of this design, like all the orthodontic mechanics according to Proffit,[25] is its extrusive nature that limits its prescription in the cases with deep-bite tendencies. Application of this force system caused a small amount of initial tooth movement; therefore, it was considered reasonable to assume a linear elastic behavior for the materials involved.

This archwire is now applied to such patients in the author's clinic, and a clinical trial based on this article will be conducted later.

In this way, an optimum method of unilateral overjet management was introduced and optimized.

CONCLUSIONS

An optimum method of management of a unilateral (asymmetric) overjet may be suggested on the basis of the findings of this study. Using an archwire with a vertical, helical, closed loop distal to the affected-side (excessive overjet) lateral incisor and an open vertical loop distal to the normal-side (normal overjet) lateral incisor, while not touching the distal surface of it and lacing the incisors, can provide the practitioner with best results.

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