

FINITE ELEMENT ANALYSIS OF RECTANGULAR WIRES FOR THE ALIGNMENT OF THE CURVE OF SPEE

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Abstract: This study aims to assess and compare the performance of different rectangular wires in the alignment of the Curve of Spee using finite element analysis. By analyzing stress distribution and tooth deformation, the study provides valuable insights into the biomechanical aspects of Curve of Spee alignment, aiding orthodontic treatment planning.

Materials and Methods: MIMICS software facilitated model design, while Ansys 19.0 performed geometric model simulations. CAD/CAM technology constructed models of mandibular teeth, periodontal ligament, alveolar bone, buccal tubes, brackets, and archwires. Mechanical elastic properties were assigned based on Young's Modulus and Poisson's ratio.

Results: Finite element analysis enabled the evaluation of stress distribution and tooth deformation. Six different rectangular archwires (0.016" x 0.022" NiTi, TMA, and stainless steel wires, and 0.019" x 0.025" NiTi, TMA, and stainless steel wires) were assessed for incremental displacement and alignment of the Curve of Spee. Force values and tooth deformations were recorded and presented in tables and figures.

Conclusion: Selecting appropriate archwire dimensions is essential for effectively aligning the Curve of Spee. Larger dimension archwires, such as the 0.019" x 0.025" stainless steel wire, may be advantageous in correcting deeper Curves of Spee. Further research and clinical studies are needed to validate these findings and consider additional factors influencing treatment outcomes.

Keywords: Curve of Spee, rectangular archwires, finite element analysis, tooth deformation, orthodontic treatment.

INTRODUCTION

The curve of Spee is a natural curvature that exists in the occlusion of the human dentition. It refers to the curvature of the occlusal plane from the cusp tips of the posterior teeth to the incisal edges of the anterior teeth.

In orthodontics, the curve of Spee plays an important role in achieving an ideal occlusion and proper alignment of the teeth. The Andrews Six Keys of occlusion, developed by Lawrence F. Andrews¹, are a set of principles that guide orthodontic treatment planning and execution. One of these keys is a flat curve of Spee.

A flat curve of Spee is desired because it helps distribute occlusal forces evenly among the teeth during biting and chewing. It promotes stability and proper functioning of the occlusion. When the curve of Spee is too pronounced or steep, it can lead to imbalances in occlusal forces, increased risk of dental wear, and potential for instability in the long term.

During orthodontic treatment, the curve of Spee needs to be carefully managed. Fixed mechanotherapy, which involves the use of brackets and archwires, applies forces to the teeth to achieve desired tooth movements. When forces are applied through the brackets, there can be a tendency for tipping of the teeth, especially if the force is not directed properly. This can be influenced by the curve of Spee, as the force may be applied away from the center of resistance of the tooth, resulting in tipping instead of bodily movement.²

Orthodontists aim to minimize any unwanted tipping by using appropriate bracket placement, archwire selection, and auxiliary techniques. By understanding the biomechanics involved, orthodontists can apply forces that encourage controlled tooth movement and avoid excessive tipping.

In summary, the curve of Spee is an important consideration in orthodontic treatment planning. A flat curve of Spee is preferred to ensure proper distribution of occlusal forces and stability in the occlusion. Proper management of forces during orthodontic treatment is essential to achieve desired tooth movements and minimize unwanted tipping.

Decreasing the depth of the curve of Spee can result in an increase in arch circumference, and this can have effects on the position and alignment of the teeth within the arch. One of the observed consequences is the proclination (forward inclination) of the lower incisors.

Baldrige's³ findings indicate that when the curve of Spee is flattened, there is a tendency for the lower incisors to become more proclined. This can be attributed to the increased arch circumference, which may create space limitations within the arch, causing the lower incisors to tip forward.

Braun and Hnat⁴ further supported this association by noting that lower incisor proclination is linked to a reduction in lower inter-canine width. As the arch circumference increases due to the flattening of the curve of Spee, the available space for the lower teeth can become limited, resulting in crowding or narrowing of the arch. This can lead to the proclination of the lower incisors as they try to find space within the arch.

To counteract the anticipated labial crown tipping and maintain proper alignment, orthodontists often utilize rectangular archwires in conjunction with the edgewise appliance. Rectangular

archwires have a larger dimension in the buccolingual (side-to-side) direction compared to round wires. The increased stiffness and control provided by rectangular archwires help to counteract the forces that can lead to excessive labial crown tipping. This allows for more controlled and desired tooth movements during orthodontic treatment.

By using rectangular archwires, orthodontists can better manage the proclination of lower incisors and maintain the desired alignment of the teeth within the arch. However, it's important to note that the selection of archwires and treatment planning should be individualized for each patient, taking into consideration the specific needs and goals of their orthodontic treatment.

Finite Element Analysis (FEA) is a numerical method commonly used to analyze the behavior of complex structures under different loading conditions. In the context of orthodontics, FEA can be employed to study the effects of orthodontic forces and tooth movements on the dentoalveolar complex.

In this study, the aim was to compare different rectangular wires during the process of levelling the curve of Spee using FEA. Leveling the curve of Spee is often done to achieve stability of functional occlusion, muscular balance, and optimal biomechanical function of the dentoalveolar complex.

By using FEA, one can simulate the forces and movements exerted by different rectangular wires and assess their effects on the dentoalveolar structures. This analysis can provide valuable insights into the stress and strain distribution within the teeth, supporting structures, and surrounding bone during the levelling of the curve of Spee.^{5,6}

Comparing different rectangular wires through FEA allows for a quantitative assessment of their biomechanical behavior and their impact on the dentoalveolar complex. This information can help in selecting the most appropriate wire type for achieving desired tooth movements while minimizing any adverse effects on the surrounding structures.

It's worth noting that FEA provides a computational simulation of the system being studied, and the results obtained should be interpreted in conjunction with clinical observations and other evidence. Nevertheless, FEA can contribute to our understanding of the biomechanics involved in orthodontic treatment and aid in the decision-making process for selecting appropriate treatment approaches.

Materials and Methods

In this study, the design and modelling of the different components were carried out using various software tools. MIMICS software was used to design the models, while Ansys 19.0 software (specifically version 14) was used for geometric model simulation and stress analysis.

The archwire and bracket systems were created using CATIA V5 R19 software, which is a computer-aided design (CAD) software. This allowed for precise modeling and representation of the orthodontic components. Additionally, CAD/CAM technology was employed for the fabrication of the physical models based on the digital designs.

The finite element models included all the mandibular teeth, periodontal ligament, alveolar bone, buccal tubes, brackets, and archwires. These models were constructed using the mechanical elastic properties of the materials, such as Young's modulus of elasticity and Poisson's ratio. The mechanical properties of the materials are important parameters in determining their behavior under applied forces.

The materials used in the models were assumed to be homogenous (uniform composition), isotropic (same properties in all directions), and linearly elastic (following Hooke's law).^{7,8}

To determine the magnitude of stress, a detailed 3-dimensional model was constructed, which included the periodontal ligament (PDL) and alveolar bone. The interface between the alveolar bone socket and the root surface was set to be 0.2 mm, which corresponds to the width of the PDL (0.25 to 0.35 mm).^{7,8}

The final meshwork of the model consisted of 6,197 nodes and 3,115 elements. Meshing is the process of dividing the model into smaller, interconnected elements to accurately represent the geometry and facilitate stress analysis. The number of nodes and elements in the mesh determines the resolution and accuracy of the analysis.

Standard edgewise prescriptions were used for all models, meaning that the brackets were positioned with no torque (rotation) or angulations. This standardization helps in comparing the effects of different archwires on the stress distribution during the levelling of the curve of Spee.

The brackets used in the models were based on computer-aided design (CAD) with a slot dimension of 0.018 × 0.025 inches. This refers to the dimensions of the slot in which the archwire is inserted. The chosen slot size is a common specification in orthodontics and is used to accommodate various types of archwires.

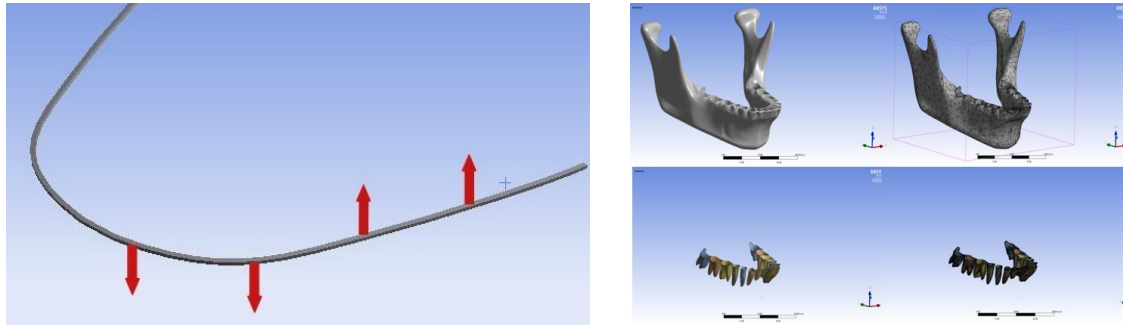
By employing these specific parameters and configurations in the model construction, the study aimed to analyze the stress distribution and evaluate the effects of different archwires on the dentoalveolar structures during the process of levelling the curve of Spee.

Six different archwires were used: 0.016 x 0.022 rectangular-shaped NiTi, TMA, and stainless steel wires, as well as 0.019" x 0.025" rectangular-shaped NiTi, TMA, and stainless steel wires. These archwires were passively placed into the bracket slots of the models.

Three models were constructed using computer-aided design (CAD) software, each representing a different inclination angle of the archwire: 90°, 100°, and 110°. These models allowed for the analysis of stress distribution on the root surfaces and periodontal ligament (PDL), as well as the

evaluation of different types of mandibular incisor movement caused by the various archwires. (Figure 1)

The deformation of the teeth was also assessed during the process of levelling the curve of Spee. Specifically, the 0.016 x 0.022" NiTi, TMA, and stainless steel wires, as well as the 0.019 x 0.025" NiTi, TMA, and stainless steel wires, were evaluated for their effects on tooth deformation. An intrusive movement in the apical direction of 0.2 mm was applied to simulate the initial displacement of the lower incisor. (Figure 2)



- Figure 1- Finite Element Model of Mandible with All Mandibular Teeth, Periodontal Ligament, Alveolar Bone
- Figure 2- The levelling of curve of Spee by displacement of the archwire in the anterior segment (intrusive) and the posterior segment (extrusive).

The levelling of the curve of Spee with various depths ranging from 2mm to 6mm was simulated. This was achieved by simultaneously displacing the archwire in the anterior segment (intrusive) and the posterior segment (extrusive) of the finite element models (FEM).

The von-Mises stress was generated at the root surface and periodontal ligament (PDL) due to the archwire's interaction with the brackets. This stress distribution provided insights into the mechanical effects on the tooth structures.

To understand the pattern of tooth movement, the Z-axis displacement in each model was investigated, which represents the movement in the anteroposterior direction. Through this analysis it was observed how the teeth responded to the simulated orthodontic forces.

Furthermore, the resultant force values obtained from this analysis were recorded and transferred to the respective finite element models to evaluate the deformation of the mandibular dentition. This assessment helped assess the structural changes and movements of the teeth during the levelling of the curve of Spee.

Results

Force values for incremental displacement and levelling the curve of spee at different rectangular wires were derived from all the 3 finite element models after simulation of 1mm displacement at the mandibular incisors model was calculated with Ansys Version 14 software. The magnitude of

Force value generated at different rectangular wires by 0.016" × 0.022" Stainless steel, TMA and NiTi arch wires and 0.019"x0.025" Stainless steel, TMA and NiTi arch wires incremental displacement of Mandibular incisors are shown in Table no. 1 and Figures 3 and 4.

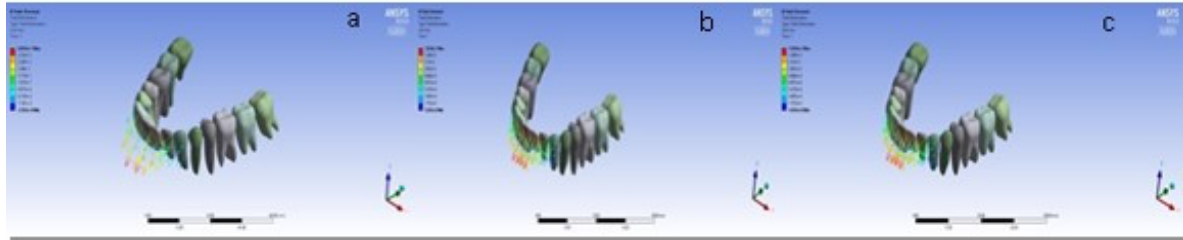


Figure 3- Force generated by levelling of various archwires

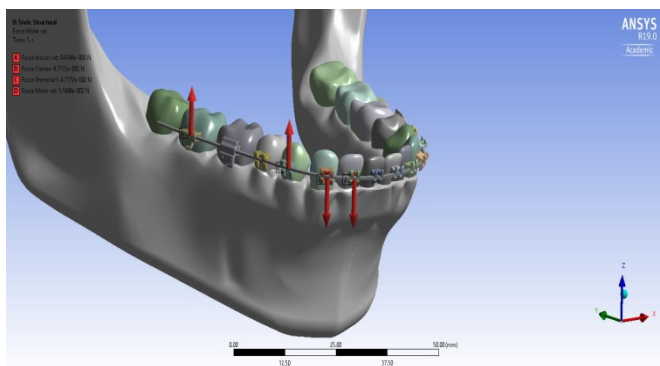


Figure 4- Deformation of teeth 1mm displacement-levelling the curve of spee (0.016x0.022 Stainless Steel wire , NiTi and TMA)

Depth of curve of spee	Deformation (mm) of mandibular teeth	
	Minimum	Maximum
0.016X0.022" SS		
2mm	3.5202e-8	2.983e-5
3mm	4.373e-8	3.5271e-5
4mm	5.0095e-8	4.0404e-5
5mm	5.6396e-8	4.5487e-5
6mm	6.4292e-8	5.1856e-5
0.019X0.025" SS		
2mm	4.0933e-8	3.30153e-5
3mm	5.0848e-8	4.1012e-5
4mm	5.8248e-8	4.6981e-5
5mm	6.5577e-8	5.2892e-5
6mm	7.4758e-8	6.0297e-5

0.016X0.022" TMA		
2mm	1.9361e-8	1.5616e-5
3mm	2.4926e-8	2.0104e-5
4mm	2.7501e-8	2.1818e-5
5mm	3.1018e-8	2.5018e-5
6mm	3.5039e-8	2.8261e-5
0.019X0.025" TMA		
2mm	2.2922e-8	1.8488e-5
3mm	2.9492e-8	2.3787e-5
4mm	3.0872e-8	2.49e-5
5mm	3.6067e-8	2.9091e-5
6mm	4.1954e-8	3.3839e-5
0.016X0.022" NiTi		
2mm	1.1448e-8	9.2334e-5
3mm	1.4221e-8	1.147e-5
4mm	1.742e-8	1.3475e-5
5mm	1.834e-8	1.4792e-5
6mm	2.0908e-8	1.6863e-5
0.019X0.025" NiTi		
2mm	1.6872e-8	1.3609e-5
3mm	2.096e-8	1.6905e-5
4mm	2.401e-8	1.9366e-5
5mm	2.7031e-8	2.1802e-5
6mm	3.0815e-8	2.4855e-5

Table 1- Deformation of the tooth - levelling of the curve of

DISCUSSION

The curve of Spee plays a crucial role in the biomechanics of occlusion, affecting how forces are distributed across the teeth during mastication. A steep curve of Spee can lead to uneven force distribution, which may cause excessive wear on certain teeth and contribute to long-term instability of the dental arch. This study's focus on levelling the curve of Spee highlights the importance of understanding and managing these biomechanical forces in orthodontic treatment.

Rectangular archwires are instrumental in orthodontic treatment due to their ability to control tooth movement more precisely compared to round wires. This study explored various rectangular archwires, namely 0.016" × 0.022" and 0.019" × 0.025" wires made from NiTi, TMA, and stainless steel. The findings suggest that the choice of archwire material and size significantly impacts the effectiveness of levelling the curve of Spee.

NiTi (Nickel-Titanium) Wires are known for their superelastic properties and shape memory, providing consistent force over various deflections. The study found that 0.016" × 0.022" NiTi wires resulted in minimal deformation, making them suitable for the initial stages of levelling a shallower curve of Spee. Their flexibility and lower stiffness help minimize unwanted tipping and provide a gentle yet effective force.⁹

TMA (Titanium Molybdenum Alloy) Wires: TMA wires offer a balance between flexibility and strength, with moderate stiffness compared to stainless steel and NiTi. They are effective in situations requiring moderate force application. The study's results showed that TMA wires produced intermediate levels of deformation, indicating their utility in progressive stages of treatment.

Stainless steel wires are the stiffest among the three types studied. The 0.019" × 0.025" stainless steel wire showed the maximum deformation, indicating its effectiveness in the later stages of treatment for deeper curves of Spee. However, their high stiffness necessitates careful application to avoid excessive force and potential damage to the periodontal ligament and alveolar bone.

Orthodontists must carefully select archwire dimensions and materials based on the specific characteristics of the patient's curve of Spee and treatment phase. The study's findings suggest that starting with more flexible NiTi wires to address shallower curves and progressing to stiffer stainless steel wires for deeper curves can optimize treatment outcomes. The incremental approach allows for controlled and precise levelling, minimizing unwanted tooth movements and ensuring better long-term stability.¹⁰

The proclination of lower incisors is a significant consideration during the levelling of the curve of Spee. Flattening the curve often increases arch circumference, which can lead to forward tipping of the lower incisors if not managed properly. This study's findings align with Baldridge and Braun's research, which also noted changes in arch length and incisor positioning with curve levelling.

Orthodontists must anticipate and counteract these changes by using appropriate auxiliary techniques, such as applying lingual crown torque or incorporating torquing auxiliary devices. Ensuring proper lower incisor positioning is critical for maintaining functional occlusion and achieving esthetic results.

The finite element analysis provided detailed insights into stress distribution across the dentoalveolar complex. The study observed that stress concentration varied with different archwire dimensions and materials, impacting tooth movement patterns. For instance, the 0.019" × 0.025" stainless steel wire generated higher stress levels, facilitating greater intrusive movements necessary for deeper curve correction.

Understanding these stress patterns helps orthodontists predict and control tooth movements more accurately, avoiding potential complications such as root resorption or periodontal damage. Incorporating these biomechanical insights into treatment planning can enhance the precision and effectiveness of orthodontic interventions.¹¹

While this study provides valuable biomechanical data, further research is needed to explore the clinical implications of these findings. Longitudinal studies involving diverse patient populations and varying clinical scenarios would help validate the results and refine treatment protocols. Additionally, investigating patient-reported outcomes, such as comfort and treatment satisfaction, can provide a holistic understanding of the impact of different archwire selections.

Emerging technologies, such as 3D printing and advanced imaging techniques, can further enhance finite element modeling, providing more accurate and patient-specific simulations. Integrating these technologies into routine practice can revolutionize orthodontic treatment planning and execution.

Conclusion

This study underscores the importance of selecting appropriate archwire dimensions and materials for effective levelling of the curve of Spee. Larger dimension wires, particularly stainless steel, are more effective for deeper curves, while smaller dimension NiTi wires are preferable for shallower curves. Maximum deformation was produced by .019"×.025" Stainless steel archwire for levelling a curve of Spee of 6mm on teeth. Minimum deformation was produced by .016"×.022" NiTi archwire for levelling a curve of Spee of 2mm on teeth. The deformation increased on teeth in ascending order with respect to NiTi, TMA, and Stainless Steel. The deformation increased on teeth with increasing dimensions.

Orthodontists must consider these factors to ensure optimal force distribution, controlled tooth movement, and long-term stability. Continued research and clinical validation are essential to enhance the precision and effectiveness of orthodontic treatments, ultimately improving patient outcomes.

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