Stress Distribution of Anterior Tooth Apex and Their Surrounding Alveolar Bone during Maxillary Anterior Intrusion on Segmented and Continuous Wires (3D Finite Element Analysis)

Christina Agustine[1], Benny Mulyono Soegiharto[1]*, Krisnawati[1]

1. Department of Orthodontics, Faculty of Dentistry, Universitas Indonesia, Jakarta, Indonesia.

Abstract

Stress distribution is one of the most important factor in understanding orthodontic tooth movement. This research aimed to analyze stress distribution of anterior tooth apex and their surrounding alveolar bone during maxillary anterior intrusion using segmented and continuous wires with various miniscrew vertical positions. Six 3D maxillary models were assembled and divided by the type of wires used (continuous and segmented wires) and three different vertical position of the miniscrew (3,5,8 mm). Simulation revealed that a statistically significant difference were found on anterior tooth apex with different miniscrew vertical position within segmented groups, but not in continuous groups (p<0.05). Meanwhile, stress generated on alveolar bone was not proportioned with the increase of miniscrew vertical position.

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Introduction

Most clinical research on maxillary anterior intrusion using miniscrew were normally conducted *in vitro*, since *in vivo* research might not be viable as they might not meet ethical clearence. Whilst, *in vitro* research might not be representative being mostly non-human bones were used, invasive and were not explaining the interaction between miniscrew and the surrounding structures. A method in engineering allowed a non-invasive approach using computer software to quantify and visualise stress distribution of an object by using 3D simulation called *Finite Element Analysis* (FEA). FEA could provide a new information regarding the interaction between teeth, supporting periodontal tissues and miniscrews when intrusion forces were applied.

This research aimed to analyze stress distribution on anterior teeth apex and their surrounding alveolar bone on a 3D simulation of maxillary anterior intrusion using segmented and continuous wires with various minisrew vertical positions. Since there has never been any similar research conducted, it was hypothesised that there was no difference of stress distribution on maxillary anterior intrusion either using segmented or continuous wires with various miniscrew vertical position.

***Corresponding author:**
Benny Mulyono Soegiharto
Department of Orthodontics
Faculty of Dentistry
Universitas Indonesia, Jakarta, Indonesia
E-mail : benny_soegiharto@yahoo.com

Methodology

A CBCT image of a dry skull were taken using I-CAT 17-19 (i-CAT, USA) and processed to make a maxillary solid model using ITK-SNAP 3.2 (PICSL & SCI, USA) and Geomagic V10.0 (Geomagic corp, USA) software. Each model's components: MBT slot 0.022” brackets (Mini Diamond, Ormco), buccal tubes for 1st and 2nd molars (GAC), 0.019x0.025 steel wire (GAC), two miniscrews (1,4x6 mm, Jeil Corp, South Korea) were assembled according to their original objects and dimensions then incorporated to the maxillary solid models using Autodesk Inventor (Autodesk Inc, USA) software. All tooth was aligned according to the wires, where anterior teeth inclination was made 110° to Palatal Plane. Six 3D maxillary models (S3, S5,S8,K3,K5,K8) were assembled and divided by the type of wires used (segmented (S) and continuous(K)) and vertical position of the miniscrew (3, 5 and 8 mm from lateral incisors CEJ).

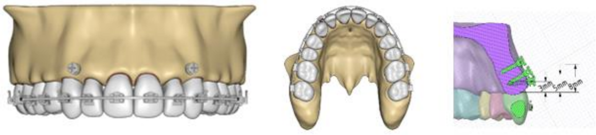

Figure 1. 3D maxillary model.

Segmented wires were placed from tooth permanent right upper second molar to right upper canine, right upper lateral incisor to left upper lateral incisors, and left upper canine to left upper second molar, whilst continuous wires were placed from tooth permanent right upper second molar to left upper second molar. A vertical bar was made in each bracket slot to mimic bracket ligation in clinical condition. Two miniscrews were placed between permanent upper lateral incisors and upper canines on both sides at 90° angulation to alveolar bone, where powerchain were attached and connected into the archwire in order to achieve bodily tooth movement.[1,2]

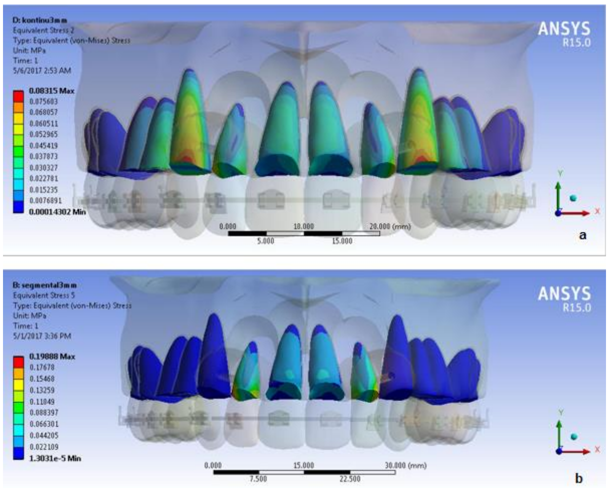

Figure 2. The difference in stress pattern (vonMS) as the result of maxillary anterior intrusion simulation using continuous (a) and segmented wires (b) with 3 mm miniscrew vertical position.

Material	Modulus Young	Poisson's Ratio
Miniscrew (Ti-6Al-4V: Titanium-6%Aluminium-4%Vanadium)[20]	113.800 MPa	0.31
Stainless steel preadjusted bracket (MBT slot 0.022") 17-4 PH[20]	197.000 MPa	0.272
0.019x0.025" Stainless steel wire 18-8[20]	193.000 MPa	0.29
Polyurethane-based elastomer (powerchain)[20]	25 MPa	0.05
Tooth[5,20]	20.300 MPa	0.30
Periodontal ligament[21,22]	0.59 MPa	0.49
Alveolar bone[5,23]	13700 MPa	0.38

Table 1. Modulus Young and Poisson's ratio of various materials used in this research.
*All materials were assumed as isotropic and linearly elastic.

There were two *Region of Interest* (ROI) in this research: maxillary incisors tooth apex and their surrounding alveolar bone. For the bone, the radius of 4.2 mm circumference the incisor tooth apex was used.[3] The total of 374.873 elements dan 676.415 nodes were created for each model. All material properties including Young's Modulus and Poisson's ratio were set, whilst boundary condition was set to zero (Table 1).

Simulation were done using ANSYS 15.0 (ANSYS Inc, USA) by applying 80 gram intrusion force, after validating the model by comparing the behaviour of each models with those in Padmawar et al (2012) research.[4–6] Analysis were done both visually and numerically.

Visual analysis was done to compare the stress pattern by identifying color map ranging from red (area with the highest stress) to blue (area with the lowest stress) for vonMS and maxPS, and inversely for minPS. Numerical analysis was done by measuring minimum of 50 nodes with the highest stress value for each stress type (vonMS/equal stress, MaxPS/1st principal stress/tensile, MinPS/3rd principal stress/compressive) on each ROI (right side only). To make sure all nodes coordinates measured in all models for each ROI were the same, 50 highest stress nodes coordinates on model S3 were set as the gold standard. They were compared to the 50 highest stress nodes coordinates on model S5. If any nodes location differences were found, a stress probing on the exact different nodes coordinates were done individually on both models and added to the data pool.

The same procedure were done for models S8, K3, K5, K8 for each ROI and each stress type, creating more than 50 nodes measured in each data pool. Since all datas had normal distribution but the variance were not homogenous, independent *t*-test were used using SPSS Statistics 20.0 (IBM, USA).

Results

The stress pattern of the ROI tooth apex seen in group S were different from group K. Unlike group S models which showed that intrusion would only affect four incisors, group K models showed that intrusion force would affect all six anterior teeth up to the second premolars.

Interestingly, MinPS simulation in this ROI for both groups showed that the labial part of the roots was the area with the highest compressive stress.

A statistically significant difference was found on vonMS, MaxPS and MinPS for ROI incisor tooth apex for each vertical miniscrew height on group S, but not in group K (Table 2).

A statistically significant difference was also found between group S and K with different miniscrew vertical position (Table 3).

Stress	Mechanics	Group	N	Mean	SD	CI 95% mean difference		*P*
						Lower	Upper	
MaxPS	Continuous	K3 K5	59 59	0.0379 0.0382	0.00277 0.00280	-0.0013	0.0006	0.504
		K3 K8	59 59	0.0379 0.0380	0.00277 0.00285	-0.0011	0.0009	0.826
		K5 K8	59 59	0.0382 0.0380	0.00280 0.00285	-0.0008	0.0012	0.659
	Segmented	S3 S5	59 59	0.1211 0.1271	0.00890 0.00967	-0.0094	-0.0026	0.001*
		S3 S8	59 59	0.1211 0.1322	0.00890 0.01071	-0.0146	-0.0074	0.000*
		S5 S8	59 59	0.1271 0.1322	0.00967 0.01071	-0.0087	-0.0012	0.009*
MinPS	Continuous	K3 K5	54 54	-0.0649 -0.0647	0.00384 0.00381	-0.0016	0.0012	0.802
		K3 K8	54 54	-0.0649 -0.0635	0.00384 0.00373	-0.0028	0.0000	0.065
		K5 K8	54 54	-0.0647 -0.0635	0.00381 0.00373	-0.0026	0.0002	0.109
	Segmentad	S3 S5	54 54	-0.1815 -0.1893	0.01108 0.01093	0.0035	0.0119	0.000*
		S3 S8	54 54	-0.1815 -0.1953	0.01108 0.01085	0.0096	0.0179	0.000*
		S5 S8	54 54	-0.1893 -0.1953	0.01093 0.01085	0.0018	0.0102	0.005*
vonMS	Continuous	K3 K5	53 53	0.0632 0.0632	0.00357 0.00354	-0.0013	0.0013	0.991
		K3 K8	53 53	0.0632 0.0622	0.00357 0.00344	-0.0003	0.0023	0.165
		K5 K8	53 53	0.0632 0.0622	0.00354 0.00344	-0.0004	0.0022	0.991
	Segmented	S3 S5	53 53	0.1782 0.1858	0.01049 0.01039	-0.0115	-0.0035	0.000*
		S3 S8	53 53	0.1782 0.1917	0.01049 0.01016	-0.0175	-0.0095	0.000*
		S5 S8	53 53	0.1858 0.1917	0.01039 0.01016	-0.0099	-0.0020	0.003*

Table 2. Independent t-test result of types of wires used (segmented or continuous) to miniscrew vertical height on simulation of maxillary anterior intrusion for ROI anterior tooth apex.
K3=Continuous 3mm. K5=Continuous 5mm. K8=Continuous 8mm. S3=Segmented 3mm. S5=Segmented 5mm. S8=Segmented 8mm. Independent t-test, p<0,05=statistically significant.

Type of Stress	Miniscrew vertical position	Group	N	Mean	SD	CI 95% mean difference		*p*
						Lower	Upper	
MaxPS	3 mm	K3 S3	59 59	0.0379 0.1211	0.00277 0.00890	-0.0856	-0.0808	0.000*
	5 mm	K5 S5	59 59	0.0382 0.1271	0.00280 0.00967	-0.0915	-0.0863	0.000*
	8 mm	K8 S8	59 59	0.0380 0.1322	0.00285 0.01071	-0.0970	-0.0913	0.000*
MinPS	3 mm	K3 S3	54 54	-0.0649 -0.1815	0.00384 0.01107	0.1134	0.1198	0.000*
	5 mm	K5 S5	54 54	-0.0647 -0.1893	0.00381 0.01093	0.1214	0.1276	0.000*
	8 mm	K8 S8	54 54	-0.0635 -0.1953	0.00373 0.01086	0.1286	0.1348	0.000*
VonMS	3 mm	K3 S3	53 53	0.0632 0.1782	0.00357 0.01049	-0.1180	-0.1120	0.000*
	5 mm	K5 S5	53 53	0.0632 0.1858	0.00354 0.01039	-0.1255	-0.1196	0.000*
	8 mm	K8 S8	53 53	0.0622 0.1917	0.00345 0.01016	-0.1324	-0.1266	0.000*

Table 3. Independent t-test results of different miniscrew vertical position to types of wires used (continuous and segmented) on simulation of maxillary anterior intrusion for ROI anterior tooth apex.
K3=Continuous 3mm. K5=Continuous 5mm. K8=Continuous 8mm. S3=Segmented 3mm. S5=Segmented 5mm. S8=Segmented 8mm. Independent t-test, p<0,05=statistically significant.

It was also evident that stress generated in group S were always higher than in group K, with both groups showed that the higher the vertical position of the miniscrew, the higher the stress value.

The stress pattern of bone surrounding tooth apex did not show any difference between all groups. But it was found that the higher the vertical position of the miniscrew, the lower the stress value on the alveolar bone surrounding the tooth apex. Statistically significant difference was found between all groups, except between model K3-K5 and K8-S8.

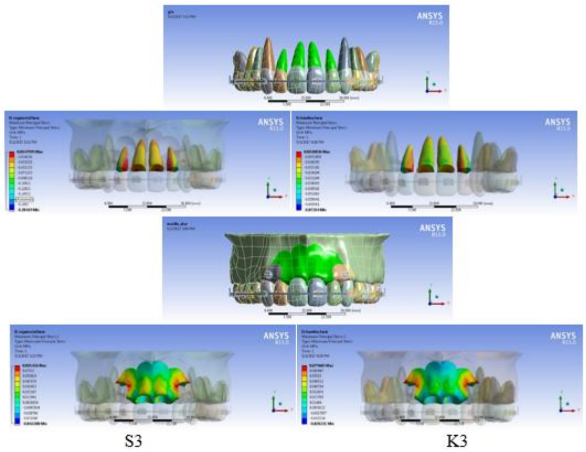

Figure 3. Simulation on maxillary anterior intrusion (minPS) between the S3 and K3 models showed a marked difference within the ROI incisor tooth apex, with the highest compressive stress were located on the labial side of incisor roots for both models. Whilst, no difference were found for ROI bone surrounding incisor tooth apex (maxPS).

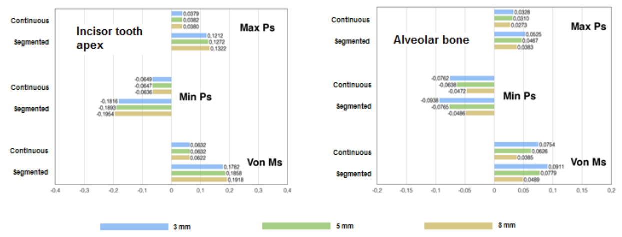

Figure 4. Graphic mean of stress value generated after simulation of maxillary anterior intrusion using segmented and continuous wires with different miniscrew vertical height.

Discussion

In this research, FEA had been proven to be able to provide additional information prospectively, both visually and numerically, on maxillary anterior intrusion using miniscrew with various miniscrew vertical height using segmented and continuous wires. However, linear FEA used in this research only provide a ‘snapshot’ of conditions on the incisor roots, alveolar bone surrounding incisor roots, miniscrew and bone surrounding miniscrew when intrusion force was applied. Thus, the stress pattern shown was not related with time and the final tooth position after intrusion.

There were three types of stress simulated in this research to show areas with the highest tensile stress (maxPS), areas with the highest compressive stress (minPS) and areas with highest equivalent stress (vonMS). Former research conducted using FEA including Ammar *et al* (2011), Liu *et al* (2012), Lee *et al* (2013), Plana *et al* (2013), Machado (2014), Kuroda *et al* (2014), Ajami *et al* (2016) only applied vonMS as the only parameter to evaluate stress distribution both in biological tissues and non-biological materials such as miniscrew.[7–12] Pollei (2009), Kanjanaouthai *et al* (2012), Duaibis *et al* (2012), Alrbata (2015) started applying maxPS and minPS mainly to evaluate stress on bone surrounding miniscrew.[13–16] In accordance to these research, it was revealed that the use of vonMS for biological tissue such as bone and tooth apex had been irrelevant. The use of maxPS and minPS to evaluate compressed and strained areas were more suitable for biological tissues. This had been in accordance with the pressure-tension theory of tooth movement, where bone apposition would occur on the tension side and bone resorption would occur on the pressure side.[1] Furthermore, Duaibis *et al* (2011) also noted that vonMS yield criterion applied best to ductile material, such as metals[15].

The difference found in the stress pattern of ROI incisor tooth apex revealed that maxillary intrusion using continuous wire affected not only four incisors tooth apex, but also extended posteriorly to the second premolars. Thus, the stress value for all stress types (maxPS, minPS and vonMS) in continuous wires group had always been lower compared to the segmented group, in regard to the fact that intrusion force were distributed to a larger number of tooth. The difference between both groups with different miniscrew vertical heights were statistically significant. Moreover, the increase of stress value on this ROI for both groups were proportioned with the increase of miniscrew vertical height. This might be explained by the amount of moment created on the same amount of force was proportioned with the increase of distance (M = F x d).[17] Statistically significant difference were also found on the segmented wire group with different miniscrew vertical height, but this was not the case in the continuous wire group. Thus, in maxillary anterior intrusion using segmented wire, miniscrew vertical position might have been an important factor to be considered.

In order to produce orthodontic movement in such a manner as to allow the periodontal ligament and alveolar bone tissue to restore normality, the root surface should have undergone stress that was slightly higher than the stress exerted by the blood in the capillary vessel (capillary blood stress) of 0.0026 MPa.[18] In this research, both the lowest maxPS and minPS of all groups showed a higher stress value than this (0,0331 and -0,0580 MPa). However, it did not mean that 80 gram of intrusion force could cause root resorption, especially to the regards of its complex and multifactorial aetiology.[19]

Theoretically, intrusion force would cause stress which concentrated on the tooth apex.[1] Whilst, an interesting finding in this research revealed that both segmented and continuous with different miniscrew vertical heights showed that stress were concentrated on the labial and mesial-distal part of the incisor roots. This might be explained by the counter clockwise moment generated by applying intrusion force using miniscrew inserted at 90° angle to the labial bone contour, which was not always perpendicular to the incisor roots (Fig 1). Although miniscrews had been inserted in the distal of lateral incisors, which were the center of resistance of four incisors, and intrusion had been done to normally-inclined incisors, these moment which might cause incisor flaring was inevitable. In other words, following the stress pattern, maxillary anterior intrusion might cause incisors flaring either by using segmented or continuous wires.

On the contrary, it was evident that on the ROI bone surrounding incisor tooth apex, the higher the position of the miniscrew, the lower the stress generated. Statistically significant differences were also found in this research between segmented and continuous wires with different miniscrew vertical heights. However, this ROI was in the close proximity with bone surrounding miniscrew. It was seen that the stress in this ROI was concentrated near the area of the bone surrounding miniscrew, far from the incisor tooth apex. Hence the influence of the stress generated on incisor tooth apex to the bone surrounding it could not be evaluated.

The drawbacks of this research were the use of assumptions which simplify the real clinical condition when maxillary anterior intrusion was done, such as miniscrew was assumed as directly contacted the alveolar bone, while in real situation there might be some gap present. However, these simplifications were also used in most previous studies using FEA. Nevertheless, the results obtained from this research could give a new insight as the base for further studies.

Many findings in this research also did not show that one mechanics is better than the other, but rather showed possible effects which might occur as a consequence of mechanical and miniscrew location of choice if maxillary anterior intrusion was about to be done. The decision to choose segmented or continuous wires, is of course, given to the clinician following the requirement of the cases.

Conclusion

From the stress distribution point of view, maxillary anterior intrusion might cause flaring, either by using segmented or continuous wires. Miniscrew vertical position needed to be considered especially if segmented wire is going to be used, in regard to the higher the miniscrew position, the higher the stress generated on incisor tooth apex. Stress generated on bone surrounding the tooth apex were not proportioned with the increase of miniscrew vertical position.

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