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Original Article

Comparative Assessment of the Orthodontic Wire's Friction Coated with Zinc Oxide Nanoparticles by Two Methods of Chemical Precipitation and Hydrothermal Process

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Abstract

Introduction: In orthodontic treatment with sliding technique, reduction of frictional forces could result in a more effective treatment. Recently, wire coating with nanoparticles were proposed to reduce frictional forces.

Aim: The aim of this study was to evaluate the effect of coating wires with zinc oxide nanoparticle by two methods of chemical precipitation and direct hydrothermal process on the wire-bracket frictional force.

Materials and methods: In this study, 30 pieces of stainless-steel arch wire with and without zinc oxide nanoparticles and 30 metal brackets with a 0.022-inch slot were divided into three groups: group 1 – control (uncoated wires); group 2 – wires coated with zinc oxide nanoparticles, and group 3 – wires with a thin layer of nanostructured zinc oxide. In the first method, the nanoparticles were made by chemical precipitation method, and in the second method, nanostructure was directly formed on wires. Additionally, SEM observations were used to confirm the presence of nanoparticles on the wires. Friction between wires and brackets was measured using Universal Testing Machine. SPSS v. 20 and ANOVA test was used in order to analyze the data. The significance level was considered as $p<0.05$.

Results: The mean value of frictional forces were 1.73 N, 1.52 N, and 1.56 N in the control group, chemical precipitation method group and thin layer of nanostructured zinc oxide group, respectively. There was no significant difference in friction rate between brackets and stainless-steel wire coated by any of these two methods ($p=0.555$).

Conclusion: Coating of orthodontic wires with zinc oxide nanoparticles can reduce friction with brackets during sliding. There was no difference in the established value of friction between coating of orthodontic wires with chemical precipitation method and thin layer coating method.

Keywords

friction, nanoparticles, orthodontic wires, zinc oxide

INTRODUCTION

Orthodontic treatment is directly associated with tooth movement. Sliding is a common mechanism for orthodontic tooth movement in which the tooth moves along a continuous arch wire. It has some reported advantages such as reduced clinical treatment procedures, patient's satisfaction, and better three-dimensional (3D) control of tooth movements.[1] However, a major concern about this technique is the wire-bracket frictional resistance which has been reported to cause a loss of 21% to 60% of the applied force.[2] This fact necessitates application of higher force level for required tooth movement which in turn increases the stress on the anchorage unit and also predisposes the roots to resorption.[3] Therefore, minimizing the frictional forces is essential for optimal tooth movement.[4] Friction can be either static or kinetic. Static friction prevents motion between two surfaces, and the movement does not start until it is overcoming and then kinetic friction opposes the direction of movement.[5] Since continuous motion of a tooth along the arch wire does not really occur, kinetic friction is not relevant in orthodontic tooth movement. According to Burrow, a quasi-static thermodynamic process occurs during sliding. There is a tipping-up righting sequence in a tooth movement and so forces and resistance to sliding change as the tooth moves along the arch wire.[5] Tipping movement begins immediately following the force application and then an angle forms between the wire and the bracket. When such an angle reaches a threshold, contact and adhesion are created between metallic surfaces of the wire and the bracket's slot. Consequently, the wire gradually undergoes notching with an ensuing plastic deformation. All of these in turn, inhibit incessant motion and causes sporadic halts in tooth movements.[6]

Various methods have been proposed to decrease the resistance to sliding including the use of several alloys for surface treatment, changing the shape and size of the wire and bracket, and coating the wire with various nanoparticles such as inorganic fullerene-like nanoparticles of tungsten disulfide (IF-WS2)[7], Teflon, and carbon nitride (CNx) films[8], and zinc oxide (ZnO).[1]

The application of nanoparticles as solid lubricants in the 1990s facilitated the diminution of frictional forces between the metallic surfaces of the wire and brackets. Since the particles have a spherical shape, a rolling effect is created between the two metallic surfaces; moreover, the nanoparticles act as spacers which prevent the contact between the two opposing surfaces.[1]

During the first stage of sliding, when there is no angle between the bracket's slot and the wire, and the bracket moves parallel to the wire, nanoparticles serve as spacers and reduce the surface irregularities.[9] Consequently, as the bracket-wire angle increase, the force at the edge of bracket gets higher and cause a greater frictional resistance in non-coated wires, while in coated wires nanoparticles get removed of the wire in the form of thin sheets which in turn can reduce the friction.[10]

Before the application of the coated metallic wires and brackets, the biocompatibility and safety of the nanoparticles should be evaluated. Biocompatible nanomaterials especially zinc oxide nanoparticles, have been used in many areas such as in catalysis[11-13], in gas sensors[14], and recently as lubricants[15,16]. Complementarily, these nanoparticles have an added advantage of possessing antibacterial properties. Altogether, the application of ZnO nanoparticles as a coating material has been recorded to exhibit antibacterial properties and reduce friction.[17,18] Since WS2 and CN has shown some cytotoxicity, ZnO nanoparticles was applied in this study.

The conventional method for coating a wire with ZnO nanoparticles is chemical solution precipitation, while a more recent approach for synthesis of ZnO nanosphere is hydrothermal process which is a direct growth of nanoparticle on the wire. Some studies have also reported the reduction in the friction of the wires coated by hydrothermal method.[19-22] However, the amount of wire-bracket friction in the orthodontic wires coated by these two methods has not yet been compared in any studies.

AIM

The aim of this study was to assess and compare the friction between stainless steel brackets and stainless steel wires which were coated with zinc oxide nanoparticles by the two methods of chemical precipitation and direct hydrothermal process.

MATERIALS AND METHODS

In this in vitro study, 30 pieces of 0.019×0.025-inch stainless steel wires (American Orthodontics, USA) and 30 standard edgewise metal brackets of upper central incisor with 0.022×0.28-inch slot size (Ultratrimm, Dentaurum, Germany) were selected. The wires and the slot of braces were cleaned in an ultrasonic bath with ethanol alcohol to remove debris from their surface and then they were evaluated by a stereomicroscope (Olympus, Japan) to detect their initial topography and that part of the wire with no structural defects were chosen for conducting the study tests. The braces with any structural defects were also substituted with better ones. The specimens were randomly divided into 3 groups. Group 1 contained 10 wires without any ZnO coating or cover which served as control group; Group 2 – ZnO nanoparticles were synthesized by the chemical solution precipitation method (conventional method); Group 3 – ZnO nanoparticles were synthesized by the hydrothermal technique (new approach for synthesis).

Wet chemical synthesis of ZnO nanoparticle

In group 2, ten pieces of wire were coated by ZnO nanoparticles synthesized by wet chemical method, with prior synthesis of the nanoparticles before the coating process. Hence, this technique can be considered as an indirect approach of coating wires. For this ZnO nanoparticles type of wire covering we used the method of Ghaemy et al.[23] The method requires the following procedures.

A 0.2 molar zinc acetate dihydrate [$Zn(CH_3COO)_2{\cdot}2H_2O$, ZnAc] (Merck Chemicals, Germany) solution in 99.5% methanol was added slowly at the rate of 5 mL/min to a solution of 1.2 M sodium hydroxide (NaOH) at room temperature. The resulting mixture was then stirred for 3 hours using a magnetic stirrer until a stable and clear solution was formed. In order to separate zinc oxide nanoparticles from the solution, centrifugation was repeated 5 times. The speed of centrifugation ranged from 7000 rpm initially and was raised to 9000 rpm as time elapsed. After each stage, in order to obtain zinc oxide powder, the precipitate was dried at 50°C. Next, an experimental tube of 50 ml ethanol solution containing 0.1 g powder of ZnO nanoparticles was transferred to the water bath at 78°C for proper mixing.[1] Uniformity and approximate size of the nanoparticles synthesized by the wet chemical process was examined via UV-Vis Spectrophotometer. The wires were then immersed in the ethanol containing solution until an even distribution of nanoparticles was achieved **(Fig. 1)**. In this method, various time intervals (10, 15, 20, 30, 40, 50, and 60 min) were chosen for coating the wires with ZnO nanoparticles. Coating of ZnO nanoparticle was confirmed by SEM images of the wires **(Fig. 2)**. Moreover, a preliminary study of frictional forces revealed that a time of 30 min was the optimum time for coating the nanoparticles.

Figure 1. The wire specimens were immersed in an ethanol solution containing ZnO nanoparticles on a magnetic mixer.

Hydrothermal method

Group 3 contained 10 wires, which were coated using the hydrothermal method. This was done according to a novel approach for fabrication of solid-phase microextraction fibers by the growth of ZnO nanowires and oriented nanorod arrays.[24,25] To do that, the following two stages were done:

1. Pre-treatment of the wires for hydrothermal method

A solution for ZnO seed layers were prepared using 0.1 M zinc acetate dihydrate [$Zn(CH_3COO)_2{\cdot}2H_2O$)] as the precursor, and ethanol as the solvent. The resultant solution was stirred for 10 min to produce a clear, transparent and homogeneous solution. For the fabrication of the seeding layer, dip coating was used by immersing the wires in the seeding solution for 1 minute and then lifting them out at a 50 mm/min rate. After dip the coating, the wires were placed in a 220° oven for 30 minutes for annealing in order to evaporate the solvent and remove the organic residues.

2. Hydrothermal synthesis of ZnO nanoparticle

For the hydrothermal synthesis the growth solution was prepared in a closed Pyrex bottle equipped with an autoclavable screw cap, by using a 100 ml aqueous solution of 0.005 M $Zn(NO_3)_2{\cdot}6H_2O$ and HMT. The resultant solution was clear and homogenous. Stainless wires were kept vertically immersed in this solution for 20 minutes at 90°C. After completion of the growth phase, the prepared wires were rinsed with DI water to eliminate residual salts or amino complexes, and in the last step, they were dried in an oven at 70°C for 20 min.

Friction test

The wires covered by both methods were subjected to a friction test. Arcs from the control group also passed the test. The test was performed according to the methods of a previous similar study[3] in the following sequence: metal brackets were ligated to the wires in a fixed position using elastomeric modules (American orthodontics, USA). The ligation method in this study was through elastomeric ligatures since this is the most common method applied by orthodontists and need less chair-time than ligation with ligature wire. Moreover, the force and the tightness of wire ligation cannot be controlled precisely in all study groups. Then wire-bracket complex was transferred to the base of universal testing machine (ZwicklRoell Z50, Germany) using a device called a fixture **(Fig. 3)**. The wires were then pulled through the bracket at a cross-head speed of 10 mm/min in a distance of 5 mm. The maximum frictional forces at the 0-degree angle between wire and bracket slot were recorded by means of the universal testing machine. In order

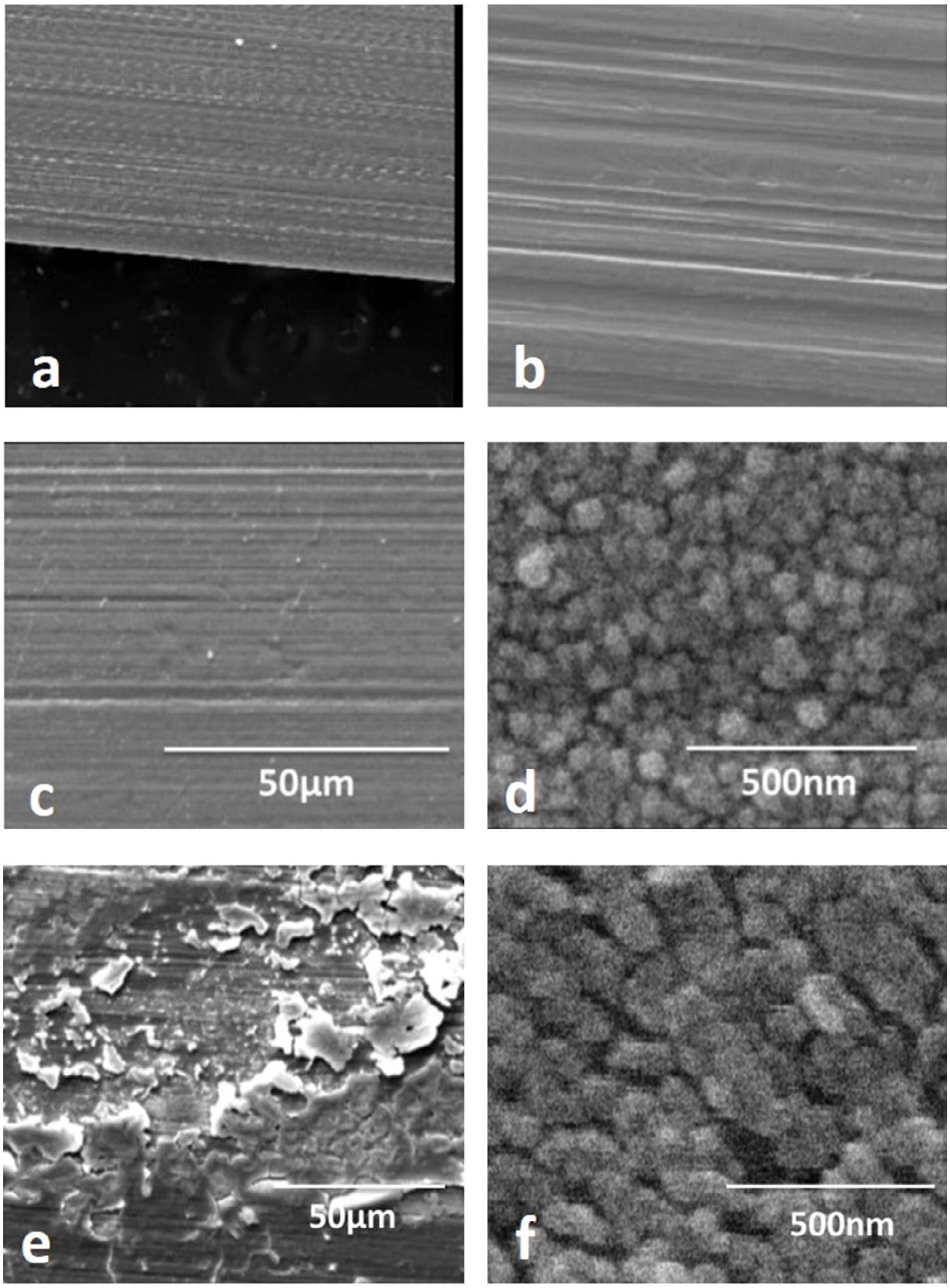

Figure 2. SEM images of the wire specimens at the scale of 50 µ and 500 µ; **a** and **b**: uncoated wire; **c** and **d**: wires coated with ZnO nanoparticles synthesized via the wet chemical method; **e** and **f**: wires coated with hydrothermal methods.

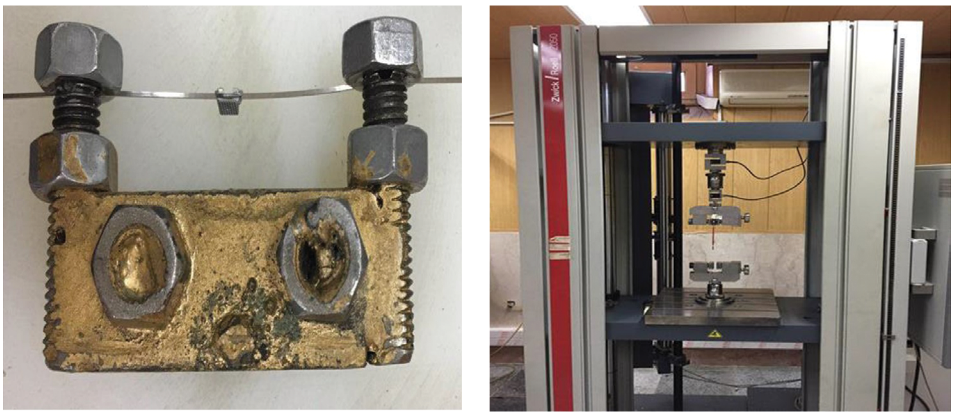

Figure 3. The wire-bracket samples were fixed and transferred to a Universal testing machine.

to have identical condition for all specimens, the brackets were changed after each wire sliding.

Statistical analysis

Statistical analysis was performed using SPSS v. 20. The mean friction force of the groups was compared using ANOVA with the level of significance set at $p<0.05$.

RESULTS

According to the UV-Vis optical absorption spectrum of ZnO nanoparticles, a peak absorbance was observed at 345 nm, which confirmed a uniform size of the ZnO nanoparticles **(Fig. 4)**. However, upon the change in the particle size or the particle shape, a slight shift in the absorption was observed.

Morphological evaluation of the surfaces of the wires

According to the SEM image, we found that using both coating methods, ZnO nanoparticles had a spherical shape with a smooth surface and even size. The wet chemical method showed ZnO nanoparticles with a size of about 100-200 nm **(Fig. 2d)**. In the other technique, in which the wires were coated with ZnO by the hydrothermal method, the particle size of the ZnO nanoparticles was about 50-60 nm **(Fig. 2f)**. The observed SEM images with a magnification of 25,000 times on the surfaces of uncoated wires and wires coated with zinc oxide nanoparticles with one of the two methods of wet chemical precipitation and hydrothermal are shown in **Fig. 2**.

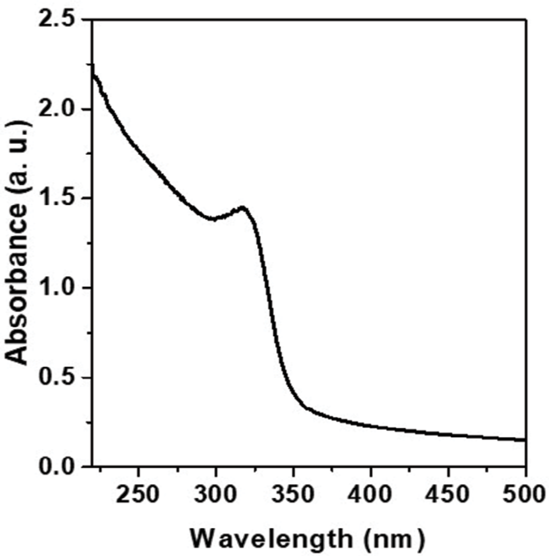

Figure 4. The absorption spectrum of a colloidal solution containing zinc oxide nanoparticles.

The measured friction of the wires

In our study, we found similar values of frictional force in the two groups of wires coated with zinc oxide (1.52 N and 1.56 N). The level of friction force in the control group of arches is slightly higher (1.733 N). The results are presented in **Table 1**. In 0.019×0.025-inch wires, a decrease in frictional force was observed at 0° angle for the ZnO-coated versus uncoated wire. However, based on ANOVA test, the friction force of the uncoated wires and the wires coated with thin layer of nanostructured ZnO (hydrothermal method) and ZnO nanoparticle (chemical precipitation method) was not significantly different ($p=0.555$).

DISCUSSION

Frictional resistance between wire and bracket is related to size, cross section, and material of the wire, ligation method, bracket width, and biological and environmental condition such as saliva, bacterial biofilm, and corrosion.[21] Recently, improving the wire-bracket interface to reduce friction has received much attention. Among different chemicals which were added to the interface of wire and brackets to reduce frictional resistance; in this study, nano ZnO was applied because of the advantages of bio-compatibility and anti-bacterial effects.[26] ZnO in nano structure can preserve a slippery surface with a friction coefficient of approximately 0.2 which is less than the previous ones. ZnO in the format of powder or compact disk is not capable to create a sliding surface.[3,16]

In the chemical precipitation method, nanoparticles were synthesized in the size of about 3 nanometer which was so small that it could preserve a continuous coating layer. In the Kachoei et al. study, the spherical nanoparticles were synthesized in the size of 20-30 nanometers.[27] In

Table 1. Frictional force of the three groups of orthodontic arch-wires with 0° bracket/wire tip angulation

Study group	Sample size	Mean frictional force N	Std. deviation	Minimum	Maximum	*P* value
Control	10	1.73	0.50	1.06	2.61	
Chemical	10	1.52	0.60	0.90	2.82	0.555
Hydrothermal	10	1.56	0.15	1.39	1.80	

N: newton

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the current study, the wires with any defect in their surface was eliminated initially. This was done since defects could act as interfering variable and it was not possible to make different study groups similar regarding to the number of superficial defects to assess the pure effect of nano-coating method on the friction. However, according to some previous studies nanoparticles act as spacers between the two opposing surfaces[1] and it is believed that they would fill the defects which in turn could reduce the friction.

The coated wires with chemical precipitation method showed a completely smooth surface, while the SEM images of the Kachoei et al.[27] and Behroozian et al.[3] studies showed surface irregularities and roughness. The frictional force of uncoated stainless steel of 0.019×0.025 wire was 1.733 N in this study, while it was 3.44 N and 2.70 N in the studies of Kachoei et al. and Behroozian et al., respectively.[1,3] This difference can be attributed to the elimination of wires with surface defect before the study. The friction force in nano-coated wires was less than uncoated wires but it was not significant. Similar pattern was reported by Behroozian et al. about the friction of porcelain brackets with stainless-steel wires coated with nano-ZnO[3] while Kachoei et al. reported a 51% reduction of friction force.

In another study, Goto et al. showed a decrease in the frictional force in SS wires with zinc oxide coating under atmospheric conditions and no change in friction under vacuum conditions.[15] They also showed that crystalline conductivity of ZnO nanoparticles has a significant effect on frictional properties. Redlich et al. on the other hand, evaluated the friction rate of 0.019×0.025 stainless steel orthodontic wires after being coated with WS2 fluorine-like nanoparticles, and observed a significant reduction in frictional force, which was in accordance with our study.[22] The difference in the friction rate of uncoated wires between the above studies and our study is due to the fact that we excluded wires with structural defects from study, which reduced the average friction of uncoated wires. Rapoport et al.[9] and Cizaire et al.[10] explained the mechanism underlying the reduction of frictional force following application of nanoparticles. In the first phase, when there is no angle between the bracket slot and the wire, when the bracket slide moves parallel to the wire, the nanoparticles act as spacers and reduce the number of superficial irregularities that interact with each other, and this in turn reduces the coefficient of friction. As the angle between the slot and the wire increases, the force increases on the slot edges and thus increases the frictional resistance of the uncoated wire.

When two stainless steel surfaces (such as uncoated wires) slide along each other, the friction coefficient increases with time probably due to a chemical oxidation reaction. In nano-coated wires, when a surface nano-layer encounters higher interfacial forces, it gets exfoliated and sliding forces occur between these thin sheets of nanoparticles, thereby reducing the coefficient of friction. Furthermore, ZnO nanoparticles act as protection against the oxidation of metal surfaces and thus reduce frictional resistance.[1] Moreover, since ZnO nanoparticles create a lubricant surface, it seems that the coating of wires with nanoparticles reduces frictional resistance due to the removal of corrosive agents.[13,18] According to Prasad et al.[17] and Zabinski et al.[16], the reduction in the coefficient of friction after ZnO coating is attributed to the nano-structural properties, which enhances the surface lubricating characteristics by their plastic deformation.

This study was conducted in in-vitro condition and intra-oral condition could not be simulated precisely. The small difference in the level of friction does not give us reason to recommend the use of zinc oxide coated arcs in orthodontic practice. It is possible that in experimental conditions the results are similar, and in clinical conditions there are larger differences. It is recommended for further studies to include an analysis of arcs of another size for example: SS 0.016×0.022″ or SS 0.017×0.025″. Moreover, an important issue about wire-bracket friction is the type of ligation. In this study, rubber ligature was applied because it is the most common mode of ligation. Other types of ligations such as metal ligature or self-ligating systems are worth further studies. It is also recommended that the effect of coating bracket's surface with ZnO nanoparticles be evaluated especially about esthetic brackets to reduce their frictional resistance.

CONCLUSIONS

According to the result of this study, coating wires with ZnO nanoparticles slightly reduce the frictional forces and resistance to sliding and this technique could be promising in taking the advantageous of low friction systems.

There was no difference between the two methods of chemical precipitation and thin layer (hydrothermal method) regarding the efficacy in reducing the friction.

Author contributions

Behrad Tanbakuchi was the advisor professor of the thesis. He developed the idea of the research and coordinated the project. Sharmin Kharrazi supervised the laboratory procedures and sample preparation. Matin Nikfarjam conducted the experiments and did the measurements. Mohammad Sadegh Ahmad Akhoundi was the co-advisor professor of the thesis and he contributed in idea development and project execution. Atefe Saffar Shahroudi participated in data analysis, drafted the manuscript and was responsible for the correspondence concerning the prepared article.

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Competing Interests

The authors have declared that no competing interests exist.

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Резюме

Введение: При ортодонтическом лечении методом скольжения уменьшение силы трения может привести к более эффективному лечению. Недавно было предложено покрытие проволоки наночастицами для снижения сил трения. Целью данного исследования было оценить влияние покрытия проволоки наночастицами оксида цинка двумя методами химического осаждения и прямого гидротермического процесса на силу трения проволоки-скобы.

Материалы и методы: В данном исследовании 30 отрезков дуг из нержавеющей стали с наночастицами оксида цинка и без них и 30 металлических брекетов с 0.022-дюймовым пазом были разделены на три группы: 1-я группа – контрольная (проволока без покрытия); группа 2 – проволока, покрытая наночастицами оксида цинка, и группа 3 – проволока с тонким слоем наноструктурированного оксида цинка. В первом методе наночастицы изготавливались методом химического осаждения, а во втором методе наноструктура формировалась непосредственно на проволоке. Кроме того, наблюдения СЭМ использовались для подтверждения присутствия наночастиц на проволоках. Трение между дугами и брекетами измеряли с помощью универсальной испытательной машины. Для анализа данных использовали SPSS v. 20 и тест ANOVA. За уровень значимости принимали $p<0.05$.

Результаты: Среднее значение силы трения составило 1,73 N, 1,52 N и 1,56 N в контрольной группе, группе метода химического осаждения и группе тонкого слоя наноструктурированного оксида цинка, соответственно. Не было существенной разницы в степени трения между брекетами и проволокой из нержавеющей стали, покрытой любым из этих двух методов ($p=0.555$).

Заключение: Покрытие ортодонтических дуг наночастицами оксида цинка может уменьшить трение брекетов при скольжении. Различий в установленном значении трения между покрытиями ортодонтических дуг методом химического осаждения и методом тонкослойного покрытия обнаружено не было.

Ключевые слова

трение, наночастицы, ортодонтические дуги, оксид цинка