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Effects of coating orthodontic archwire by zirconia nanoparticles on orthodontic tooth movement

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Abstract

Background: *To reduce the duration of orthodontic therapy, it has become necessary to accelerate orthodontic tooth movement. This reduces the risks that could arise throughout the extended course of treatment. Orthodontic friction is defined as the engagement of the archwire with bracket slot and the ligation. Thus, one of the primary objectives of biological orthodontic tooth movement is to reduce friction. One technique to reduce frictional resistance is orthodontic archwire coating, which modifies archwire surface characteristics. Several tactics have been devised for wire coatings. However, nanotechnology is one of the technologies that was introduced in the field of orthodontics.* ***The aim of the study*** *aimed to determine whether zirconium dioxide nanoparticles coated orthodontic appliances demonstrate less friction in vitro than non-coated orthodontic appliances.* ***Material & method:*** *The study was performed on sixty sample. The specimens were randomly divided into four groups. Group 1: is the control group using conventional archwires with convention uncoated brackets; Group 2: both the archwires and brackets are coated; Group 3: coated archwire only with uncoated bracket; and Group 4: coated brackets only with conventional archwire. Each group was tested under dry and wet conditions. The resistance to sliding was measured using a universal testing machine.* ***Results:*** *There was a statistically significant difference between G1 and G2, G3, and G4 in terms of frictional resistance under both wet and dry conditions. With high friction in G1 and the lowest friction in G3 and G4. There was no significant difference between the dry and wet conditions in the same group.*

Conclusion: *Although clear conclusions on in the clinical performance effectiveness have yet to be determined, these preliminary data indicate that the experimental zirconia-coated nickel titanium orthodontic archwires cause less friction. To find out if these coated archwires have a clinically significant impact on therapy effectiveness, randomized controlled clinical trials are required.*

Key words: *orthodontic wire coating, zirconium dioxide, friction, frictional resistance, nanoparticles, nanotechnology*

Conflict of Interest declaration: *The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.*

Introduction

To reduce the duration of orthodontic therapy, it is necessary to accelerate orthodontic tooth movement. [1] There are a lot of attempts, proposed methods

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and techniques aim for reducing treatment duration thus lessen the risks of gingival inflammation and enamel decalcification that could arise during the prolonged treatment. [2], [3]

Accordingly, accelerating orthodontic tooth movement to shorten the treatment period is mandatory, not only to decrease the hazards that may occur during the long treatment period but also to maintain adult patients' motivation throughout the treatment until the finishing stage. [4] As a result, researchers have investigated whether it is possible to move the teeth more quickly than with traditional techniques, either by changing the application materials, using different designs, using more aggressive methods such as surgical-assisted orthodontic tooth movement, or using chemicals and medications such as prostaglandins (PGs), hormones, or vitamins, either injected locally or delivered systemically. [5]

The interaction between the wire, ligature system, and bracket slot is known as orthodontic friction. [6] Thus, one of the primary objectives of biological orthodontic tooth movement is to reduce friction. Many tactics have been proposed to reduce the frictional resistance, including different appliance designs, ligation techniques, and mechanical protocols. [7] One of these strategies involves coating and modifying the surface of orthodontic metallic wires using a variety of techniques and materials. Nanotechnology is one of the greatest and most useful technologies that has entered the medical industry for materials manufacturing procedures. [8] A wire coating was developed to strengthen the mechanical and biological properties of the surfaces of materials used in orthodontics. The application of coatings of a material with superior properties over the surface of orthodontic archwires using various methods can improve the overall archwire properties. Depending on their intended use, coatings come in a variety of forms. The purpose of coating orthodontic archwires is to influence the surface features, which in turn affect the properties of the archwires, including thickness, bacterial adherence, corrosiveness, mechanical and frictional capabilities, and coating stability. Various materials and coating methods have been applied to improve the surface characteristics. [9] Owing to a few reported coating issues, such as coating wear and delamination, research is still being conducted to identify suitable materials and methods to increase the coating ability of various materials. Nanotechnology is a technique used to enhance the coating of wire materials. [10]

Materials are classified as nanoparticles when their particles size is below 100 nm with a minimum of one dimension. [11] Nanomaterials are different from other materials in that compared to larger particles, they have a significantly higher surface area. Therefore, changes in the mechanical, physical, and chemical properties were included. [12] It has been claimed that over 3500 dental materials contain nanoparticles that can be obtained from metals, polymers, or ceramics. [13] Noble metals such as gold, copper, platinum, and silver, as well as metal oxide nanoparticles such as magnesium oxide, iron oxide, zinc oxide, titanium dioxide, silicon dioxide, and zirconium dioxide are the most frequently used nanoparticles in dentistry and orthodontics. [14], [15] Application of surface nano coatings to orthodontic brackets, archwires, and aligners has become progressively relevant in recent years. These coatings function as dry lubricants, eliminating the requirement for liquid lubrication and effectively reducing the friction between the two sliding surfaces. Furthermore, as discussed previously, nanoparticles reduce friction by producing a smooth surface. [16]

Materials and methods:

Four brackets were attached on a metal rod allowing a 0.018-in stainless steel wire attached to an opposite rod with a bracket that was placed passively with the wire and the rest of the brackets. The wire was ligated to the bracket using elastomeric ties to standardize ligation. Resistance to sliding was measured over seven millimeter distance by the universal testing machine (Universal testing machine-model: Instron Industrial products, USA-Norwood, Materials Department, Minia University) with a fifty Newton load cell and a crosshead speed of five mm/min. Straight stainless 0.018-inch steel wire were cut into three centimeter long.

Brackets used were with slot size 0.022×0.028 inch stainless steel standard edgewise brackets with no torque or tip built in the slot or the base of the brackets. All wires and brackets were cleaned with ethanol as provided before examination. Two metal rods were made by engraving the width of the bracket down to the center of the rod. An individual metal bracket was placed in the engravement on one plate. The rod allowed the straight wire to be engaged to all the five brackets and passively centered in all bracket slots. The peak force needed to start movement was used to calculate the initial resistance to sliding that is recorded as static resistance to sliding, and the force at five millimeter of wire/bracket sliding was used to calculate the kinetic resistance to sliding.

Ethical approval:

Research Orthodontic Department of the Faculty of Dental Medicine, Minia University. This study was approved by the Scientific Research Ethics Committee of the Faculty of Dentistry, Minya University (RHDIRB2017122004).

Sample size calculation:

The sample size calculation revealed that at least 15 samples were required for each group (effect size = 0.8, α = 0.05, 1-β = 0.90). For each group, fifteen tests were conducted in both dry and wet settings.

Blinding:

This was a double-blind study in which the sample preparation group was coded by a supervisor. The researcher and statistical outcome assessments were blinded.

Grouping:

Group 1: is the control group using conventional archwires with convention uncoated brackets; Group 2: both the archwires and brackets are coated; Group 3: coated archwire only with uncoated bracket; and Group 4: coated brackets only with conventional archwire. Each group was tested under dry and wet settings.

Statistical analysis:

Data were analyzed using the Statistical Program for Social Science (SPSS) version 24. Qualitative data were expressed as frequencies and percentages. Quantitative data are expressed as mean ±SD. Mean (average): The central value of a discrete set of numbers, specifically the sum of values divided by the number of values. Standard deviation (SD) is the measure of dispersion of a set of values. A low SD indicates that the values tend to be close to the mean of the set, whereas a high SD indicates that the values are spread out over a wider range.

The following tests were done:

- Independent sample T test (T): comparing two groups (for normally distributed data).
- One-way analysis of variance (ANOVA) was used to compare more than two groups (normally distributed data).
- Post-hoc test (LSD) Least significant difference was used for multiple comparisons between different variables.

Probability (*P value*): < 0.05, considered significant; < 0.001, highly significant; and > 0.05, insignificant.

Results:

The primary objective of this in vitro study was to isolate all variables that might affect the results, to accept or refuse the null hypothesis of the research. The null hypothesis (H0) of the in-vitro part of the research was: "Coating orthodontic archwires and orthodontics brackets with zirconium dioxide nanoparticles will not affect friction resistance" The alternative hypothesis (Ha) was "Coating orthodontic archwires and orthodontics brackets with zirconium dioxide nanoparticles will reduce friction resistance"

- **Comparison between studied groups as regard studied data:**

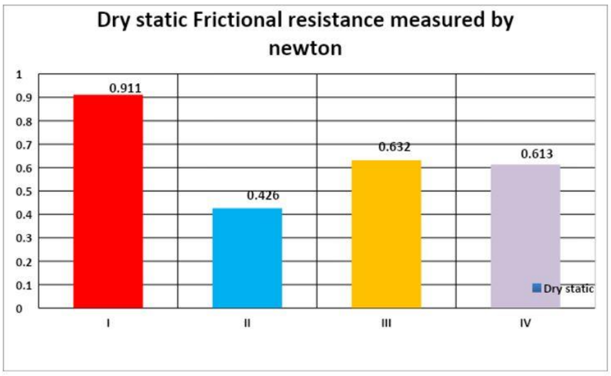
The study revealed a high statistically significant difference (*p value* < 0.001) between the studied groups regarding dry static frictional resistance measured in Newtons. It was 0.911 ± 0.066 in group I, 0.426 ± 0.049 in group II, 0.632 ± 0.053 in group III and 0.613 ± 0.065 in group IV. A high statistically significant difference (*p value* < 0.001) was observed between the studied groups regarding dry kinetic frictional resistance measured in Newtons. It was 0.828 ± 0.066 in group I, 0.365 ± 0.049 in group II, 0.577 ± 0.065 in group III and 0.561 ± 0.066 in group IV. A high statistically significant difference (*p value* < 0.001) was observed between the studied groups regarding wet static frictional resistance measured in Newtons. It was 0.875 ± 0.062 in group I, 0.406 ± 0.044 in group II, 0.592 ± 0.073 in group III and 0.589 ± 0.077 in group IV. A high statistically significant difference (*p value* < 0.001) was observed between the studied groups regarding wet kinetic frictional resistance measured in Newtons. It was 0.792 ± 0.070 in group I, 0.320 ± 0.034 in group II, 0.562 ± 0.080 in group III and 0.529 ± 0.080 in group IV. This is summarized in (Tab. 1)

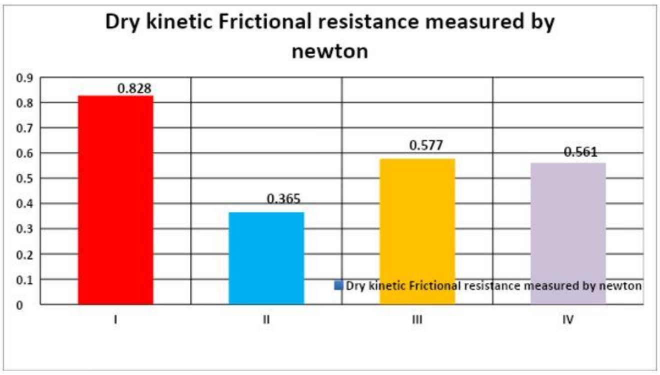
		Groups				F	P-value
		I (n = 15)	II (n = 15)	III (n = 15)	IV (n = 15)		
Dry static	**Mean**	0.911	0.426	0.632	0.613	**174.1**	**< 0.001 HS**
	±SD	0.066	0.049	0.053	0.065		
Dry kinetic	**Mean**	0.828	0.365	0.577	0.561	**143.5**	**< 0.001 HS**
	±SD	0.066	0.046	0.065	0.066		
Wet static	**Mean**	0.875	0.406	0.592	0.589	**132.2**	**< 0.001 HS**
	±SD	0.062	0.044	0.073	0.077		
Wet kinetic	**Mean**	0.792	0.320	0.562	0.529	**119.1**	**< 0.001 HS**
	±SD	0.070	0.034	0.080	0.080		

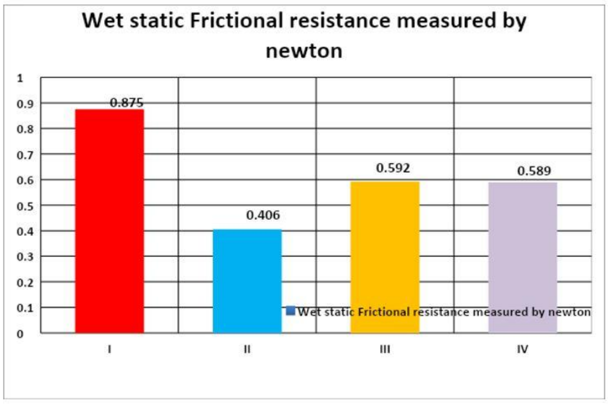
F: F value of the ANOVA test. HS: $p < 0.001$ was considered highly significant.

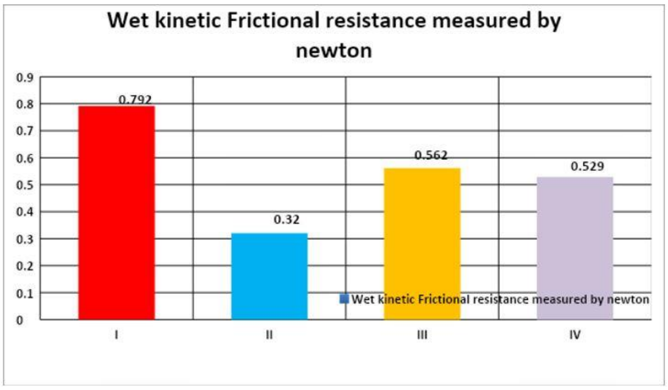
Table (1): Comparison between studied groups as regard studied data.

Bar charts show comparisons between studied groups regarding friction examination under different conditions of resistance measured by Newton.









- **The conclusion of the results was:**

1. G1 showed the highest frictional resistance, with a statistically significant difference (*P value* <0.001) between all groups.

2. G2 showed the lowest frictional resistance with a statistically high significant difference (*P value* <0.001) between G1 and statistically difference (*P value* <0.05) between G2 and G3.

3. G3 and G4 showed statistically no difference between each other.

4. There were no differences between dry and wet conditions.

5. Statistically significant differences were observed between the static frictional resistance and kinetic frictional resistance (*P value* <0.001) the highest value related to the static frictional resistance.

Discussion:

Our research question was "Does ceramic nanoparticles coating improves the clinical performance of orthodontic archwires and orthodontic brackets?". Therefore, the aim of this in vivo randomized clinical trial was to conduct a split-mouth study, measure the rate of canine retraction, and compare canine retraction rates in different cohorts of patients. The clinical importance of ceramic nanoparticle wire coatings in clinical practice was investigated in this study. The null hypothesis (H_0) of the of the research was: "coating orthodontic archwires and orthodontics brackets with zirconium dioxide nanoparticles will not affect canine retraction rate." The alternative hypothesis (H_a) was "coating orthodontic archwires and orthodontics brackets with zirconium dioxide nanoparticles will increase rate of canine retraction".

Coating orthodontic archwires enhances archwire qualities, including surface topography, frictional resistance, tarnish and corrosion resistance, antibacterial properties, and esthetics of the wires. Several studies have focused on novel coatings to cover orthodontic archwires and brackets with various materials. In this study, zirconium dioxide was the material of choice. Zirconium dioxide, also referred to as zirconia, is a white crystalline particle with excellent thermal and mechanical properties. It displays excellent mechanical and aesthetic qualities, as well as remarkable biocompatibility. It has become popular in all dental fields, such as in the manufacturing of orthodontic brackets, implant abutments, crowns, and bridges. [22]

Following a review of the literature, it was determined that nearly all in vitro studies found that coating orthodontic archwires with various materials improved frictional resistance. [23] All research, however, has suggested the use of coated orthodontic wires in standard clinical orthodontic procedures after in vivo human clinical trials. Accordingly, the present study was conducted.

Friction occurs due to microscopical interaction of different materials microstructure, such as electrons, protons, atoms, and molecules. [24]

Orthodontic friction falls under the category of dry friction and is caused by contact of the wire, ligature, and bracket slot. The relative lateral motion of the two solid surfaces in contact was resisted by the dry friction. Only the microscopic peaks on the surfaces make contact when two materials slide over one another. These peaks are referred to as asperities. There are two types of dry friction: kinetic and static friction. [25]

The friction between different solid materials that do not move in relation to each other is defined as “static friction”. Its magnitude is necessary for starting the motion before it moves. For description the movement of two objects relative to one another it is defined as “kinetic friction”. Kinetic friction is less significant in the field of orthodontics because there is no continuous motion of teeth along the archwire. Orthodontic motion occurs at a very slow rate that is less than one millimeter in a month, which approaches a scenario where static friction is more representative for the process. [25]

There is more involvement in resistance to tooth movement than friction. The resistance of tooth movement can be divided into three distinct elements: The first element is the "classical friction," which is further separated into kinetic and static friction and occurs between the wire and bracket surfaces. The next part is the "binding" that takes place when a wire is bent, or a tooth is tipped to contact the bracket's edge. The third element is "notching," which is a denting of the wire that stops the teeth from moving until the notch is released at the junction of the wire and bracket. Consequently, the combined effects of binding, notching, and friction are equal to resistance to tooth movement. [26]

In the design of a research module to study friction in vitro, friction can be studied in passive or active configurations. When the contact angle between the bracket slot and the archwire is smaller than a critical contact angle, passive configurations occurs. Because binding and notching do not occur when a passive arrangement is used, slide mechanics are only controlled by classical friction.

Friction becomes less significant as the contact angle between the wire and bracket increases, whereas binding and notching become more powerful factors that interfere with movement. Sliding mechanics are solely affected by classical friction when the contact angle between the orthodontic archwire and the long axis of brackets slot is less than 3.7°. [26]

Although friction is a straightforward orthodontic component to research, it can be challenging to do so in a way that accurately simulates the intraoral experience. Although techniques for investigating friction in vivo have been established, most research is based on in vitro investigations because of their more straightforward nature.

<u>Limitations of in vitro studies:</u> Research carried out in vitro has various drawbacks. First, most studies are passive systems that only measure friction after the binding and notching components are eliminated. In these experiments, a bracket was mounted such that the wire was dragged through it exactly parallel to the slot, creating no angle between the wire and the bracket. All these measures are the

friction that exists between the ligature, bracket, and wire.

Advantages of in vitro studies: These investigations have the benefit of determining the precise amount of friction caused by the wire, bracket, and ligature type, without the need for additional variables. The drawback is that brackets are frequently positioned in ways that are passive toward one another in clinical settings.

Some authors have reported that resistance to sliding increases as the contact angle between the bracket and archwire increases and this finding has been confirmed in multiple studies. (27) as in a study comparing resistance to sliding in passive versus active configurations, was performed with various bracket and archwire materials. When the angle between the slot axis of the bracket and the wire is more than 3 degrees, the binding overtook friction. It was observed that in the case of a stainless steel wire in a ceramic bracket, binding accounted for up to eighty percent of the resistance to sliding when the contact angle was seven degrees and up to Ninety-nine when the contact angle was thirteen degrees°. (28)

Owing to the importance of binding in the study of resistance to sliding a component with different angulations between the wire and bracket slot has been added in numerous friction tests due to the significance of binding as a variable that play an important factor during tooth movement. (29)

A secondary constraint of passive in vitro friction research is the lack of slight alterations or disruptions that are typically caused by different oral functions. Random, small movements occur within orthodontic appliances during speech, chewing, swallowing, or contact with food or tissues. These motions caused the archwire to shift in the bracket slot. It has been demonstrated that this movement modifies the appliance friction. One study attempted to measure this aspect. They mounted brackets at different angles and pulled orthodontic arch wires of different sizes through them using an Instron while applying simulated oral perturbations. They discovered that disturbances resulted in the frictional resistance briefly decreasing to zero. (30)

When the in vitro studies were stimulated with these perturbations, variables such as bracket angulation, archwire/slot clearances, and ligature did not have a detectable impact on friction. These friction reductions could play a major role in the equation if the average frequency of masticatory interactions was between 32 and 80 cycles per minute. The binding and notching at the bracket/archwire interface were momentarily removed, resulting in the resistance being lowered to zero.

These investigations demonstrated that the bulk of prior in vitro frictional resistance experiments do not accurately reflect the mode of frictional resistance that may occur in the oral cavity, and that small motions at the bracket/arch wire interface that occurs in repetitive cycles for a long period significantly reduced, if not eliminated, frictional resistance. This happens periodically when a person chews, speaks, swallows, and when their tissues and food contact with an orthodontic appliance.

As with most studies, the wide heterogeneity in methodologies makes direct comparison among these studies difficult. There are many different types of brackets, numbers of brackets, wire sizes, coating materials, types and timing of lubrication, and machine sizes and settings used in the literature. In addition, there are no systematic reviews pertaining directly to the different types of ceramic nanoparticles coated wires and their effects on friction. Owing to these discrepancies in methodology and the lack of high levels of evidence, no definite conclusions can be made on which coating materials have the lowest level of friction and if it has clinical significance. Therefore, in almost all studies, it was recommended to conduct controlled clinical trials to measure the significance of wire coating regarding the rate of tooth movement.

Conclusion

This study suggests that zirconia-coated nickel titanium orthodontic archwires create less friction than non-coated appliances. Therefore, more clinical trials are recommended to study the behavior of coated wires under different conditions, and it is important to navigate the clinical behavior with different research modules.

References

1) Tsichlaki A, Chin SY, Pandis N, Fleming PS. How long does treatment with fixed orthodontic appliances last A systematic review. Am J Orthod Dentofacial Orthop. 2016;149(3):308–318.

2) Pinto AS, Alves LS, Maltz M, Susin C, Zenkner JEA. Does the duration of fixed orthodontic treatment affect caries activity among adolescents and young adults? Caries Res. 2018;52(6):463–467

3) Pacheco-Pereira C, Pereira JR, Dick BD, Perez A, Flores-Mir C. Factors associated with patient and parent satisfaction after orthodontic treatment a systematic review. Am J Orthod Dentofacial Orthop. 2015;148(4):652–659

4) Talic NF. Adverse effects of orthodontic treatment: A clinical perspective. *Saudi Dent J*. 2011;23(2):55-59. doi: 10.1016/j.sdentj.2011.01.003

5) Haliloglu Ozkan T, Arıcı S, Özkan E. Acceleration of Orthodontic Tooth Movement: An Overview. Anatolian Clin. 2018;23(2):121-8.

6) El-Angbawi A, McIntyre G, Fleming PS, Bearn D. Non-surgical adjunctive interventions for accelerating tooth movement in patients undergoing orthodontic treatment. Cochrane Database of Systematic Reviews 2023, Issue 6. Art. No.: CD010887. DOI: 10.1002/14651858.CD010887.pub3.

7) Burrow JS. Friction and resistance to sliding in orthodontics: A critical review. Am J Orthod Dentofacial Orthop 2009; 135:442-7.

8) Zakrzewski W, Dobrzynski M, Dobrzynski W, et al. Nanomaterials Application in Orthodontics. Nanomaterials (Basel). 2021;11(2):337. Published 2021 Jan 28. doi:10.3390/nano11020337

9) Bącela J, Łabowska MB, Detyna J, Zięty A, Michalak I. Functional Coatings for Orthodontic Archwires-A Review. Materials (Basel). 2020;13(15):3257. Published 2020 Jul 22. doi:10.3390/ma13153257

10) Bayda S, Adeel M, Tuccinardi T, Cordani M, Rizzolio F. The History of Nanoscience and Nanotechnology: From Chemical-Physical Applications to Nanomedicine. Molecules, Volume:25, Issue: 1, (2019)

11) Boverhof DR, Bramante CM, Butala JH, Clancy SF, Lafranconi M, West J, et al. Comparative assessment of nanomaterial definitions and safety evaluation considerations. Regulatory Toxicology and Pharmacology. 2015;73(1):137-150. DOI: 10.1016/j.yrtph.2015.06.001

12) Bhardwaj A, Bhardwaj A, Misuriya A, Maroli S, Manjula S, Singh AK. Nanotechnology in dentistry: Present and future. Journal of International Oral Health. 2014;6(1):121-12

13) Chaughule RS, Raorane D, Pednekar S, Dashaputra R. Nanocomposites and their use in dentistry. In: Chaughule RS, editor. Dental Applications of Nanotechnology. 1st ed. Switzerland: Springer; 2018. pp. 59-79. DOI: 10.1007/978-3-319-97634-1_4

14) Slavin YN, Asnis J, Hafeli UO, Bach H. Metal nanoparticles: Understanding the mechanisms behind antibacterial activity. Journal of Nanobiotechnology. 2017;15(1):65. DOI: 10.1186/s12951-017-0308-z

15) Ferrando-Magraner E, Bellot-Arcis C, Paredes-Gallardo V, Almerich-Silla JM, Garcia-Sanz V, Fernandez-Alonso M, et al. Antibacterial properties of nanoparticles in dental restorative materials. A systematic review and meta-analysis. Medicina (Kaunas). 2020;56(2):55. DOI: 10.3390/medicina56020055

16) Maliael MT, Jain RK, Srirengalakshmi MJW. Effect of nanoparticle coatings on frictional resistance of orthodontic archwires: A systematic review and meta-analysis. World Journal of Dentistry. 2022;13(4):417-424. DOI: 10.5005/jp-journals-10015-2066

17) Matsunaga, J., Watanabe, I., Nakao, N. *et al.* Joining characteristics of titanium-based orthodontic wires connected by laser and electrical welding methods. *J Mater Sci: Mater Med* 26, 50 (2015). https://doi.org/10.1007/s10856-015-5391-9

18) Syed SS, Kulkarni D, Todkar R, Bagul RS, Parekh K, Bhujbal N. A novel method of coating orthodontic archwires with nanoparticles. J Int Oral Health. 2015;7(5):30-33

19) Fidaa Wazwaz, Jadbinder Seehra, Guy H. Carpenter, Spyridon N. Papageorgiou, Martyn T. Cobourne, Duration of canine retraction with fixed appliances: A systematic review and meta-analysis, American Journal of Orthodontics and Dentofacial Orthopedics, Volume 163, Issue 2, 2023, Pages 154-172, ISSN 0889-5406,

20) Frost, Harold M. (1983) "The Regional Acceleratory Phenomenon: A Review," *Henry Ford Hospital Medical Journal:* Vol. 31: No. 1, 3-9.

21) Stucki S, Gkantidis N. Assessment of techniques used for superimposition of maxillary and mandibular 3D surface models to evaluate tooth movement: a systematic review. Eur J Orthod. 2020;42(5):559-570. doi:10.1093/ejo/cjz075

22) Zhang R, Han B, Liu X. Functional Surface Coatings on Orthodontic Appliances: Reviews of Friction Reduction, Antibacterial

Properties, and Corrosion Resistance. *International Journal of Molecular Sciences*. 2023; 24(8):6919. https://doi.org/10.3390/ijms24086919

23) P I, Singh D, Sharma VK, Shukla NK, Chaturvedi TP. The effect of various nanoparticle coating on the frictional resistance at orthodontic wire and bracket interface: A systematic review. *J Orthod Sci*. 2022; 11:7. Published 2022 May 4. doi: 10.4103/jos.jos_152_21

24) Mantel, Alison, "Friction Testing of a New Ligature" (2011). Master's Theses (2009)

25) Burrow JS. Friction and resistance to sliding in orthodontics: A critical review. Am J Orthod Dentofacial Orthop 2009; 135:442-7.

26) Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. Eur J Orthod 1999; 21:199-208

27) Nicolls J. Frictional forces in fixed orthodontic appliances. Dent Pract Dent Rec 1968; 18:362-6.

28) Articolo LC, Kusy RP. Influence of angulation on the resistance to sliding in fixed appliances. Am J Orthod Dentofacial Orthop 1999; 115:39-51

29) Franchi L, Baccetti, T. Forces released during alignment with a preadjusted appliance with different types of elastomeric ligatures. Am J Orthod Dentofacial Orthop 2006; 129: 687-90.

30) Braun S, Bluestein M, Moore BK, Benson G. Friction in perspective. Am J Orthod Dentofacial Orthop 1999; 115:619-27